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REPETITIVE PULSE LASER DATA AND PERMISSIBLE EXPOSURE LIMITS.(U)
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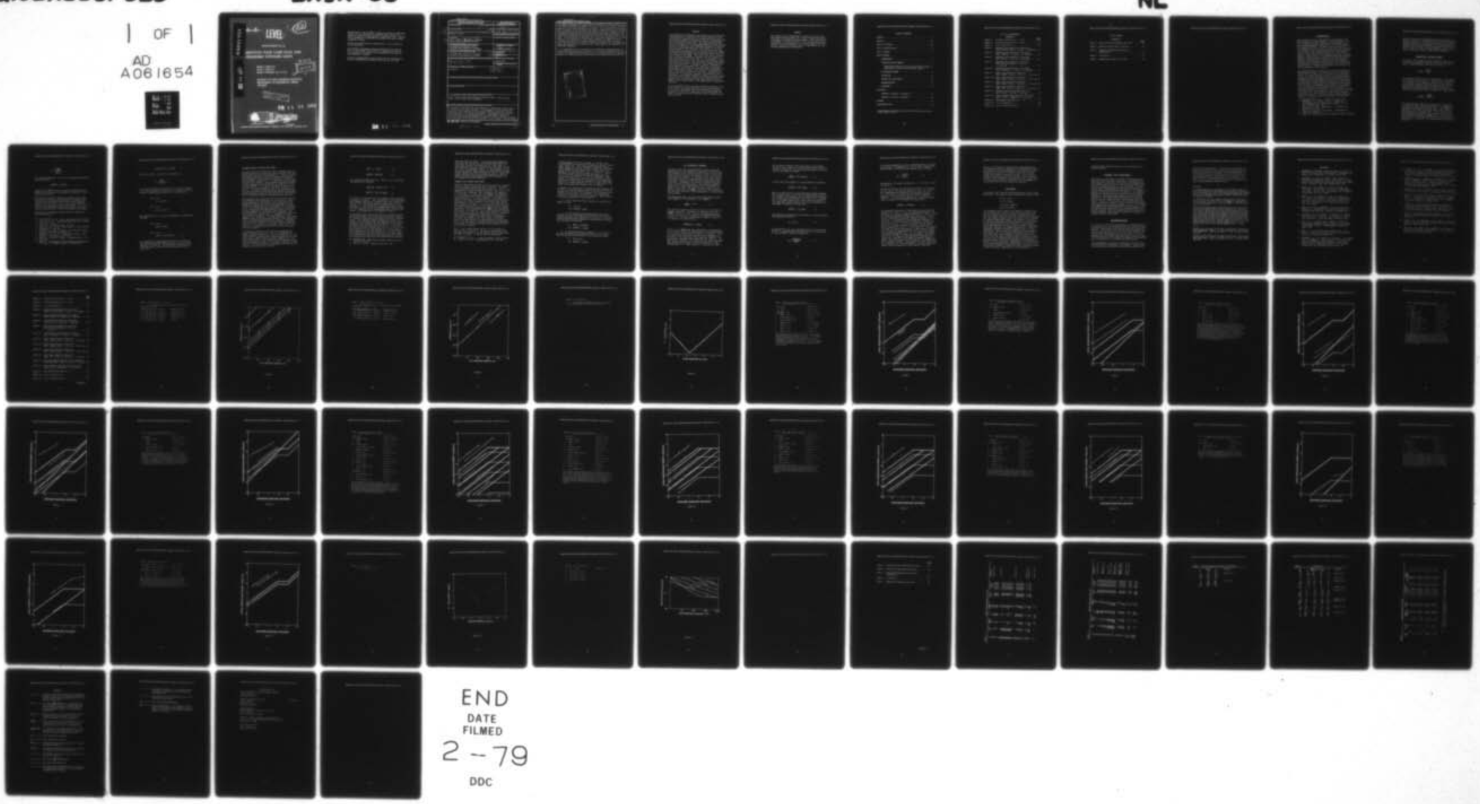

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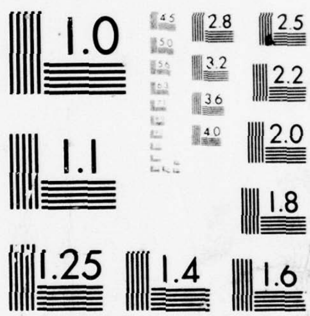
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INSTITUTE REPORT NO. 58

REPETITIVE PULSE LASER DATA AND PERMISSIBLE EXPOSURE LIMITS

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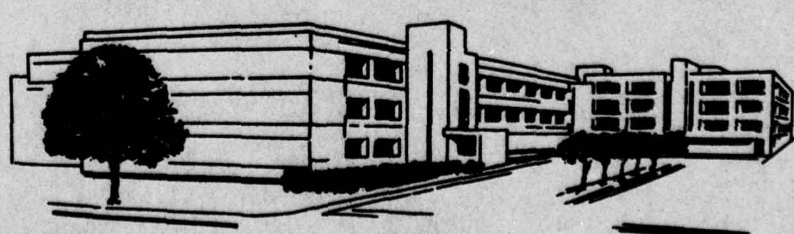
DEPARTMENT OF BIOMEDICAL STRESS
APRIL 1978



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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER (rept.)
4. TITLE (and Subtitle) (6) Repetitive Pulse Laser Data and Permissible Exposure Limits.		5. TYPE OF REPORT & PERIOD COVERED (9) Final 1 Sep 77- 31 Mar 78
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) Bruce E. Stuck, ~~MS~~, David J. Lund, BS, Edwin S. Beatrice, M.D., LTC, MC		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Non-Ionizing Radiation Division, Department of Biomedical Stress, Letterman Army Institute of Research, Presidio of San Francisco, CA 94129		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS (16) 62772A 3A762772A813 021
11. CONTROLLING OFFICE NAME AND ADDRESS Letterman Army Institute of Research, Presidio of San Francisco, CA 94129		12. REPORT DATE (11) May 1978
		13. NUMBER OF PAGES 62
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) (14) LAIR-58		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Unlimited (12) 72p.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Laser, Maximum Permissible Exposures, Repetitive Pulse, Ocular Effects, Retina, Laser Safety, Safety Standards

ED (sub 50)s

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Two methods are described for the calculation of permissible ocular exposure to repetitive pulse laser radiation. The rationale for these methods (the correction factor method and the alternate method) is based upon available experimental data from several laboratories. The ED_{50}s (effective dose for 0.50 probability of an ophthalmoscopically visible retinal lesion) for repetitive pulse exposures expressed in terms of the total intraocular energy are proportional to the pulse train duration to the 3/4 power. The continuous

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wave ED_{50}s exhibit the same dependence on the exposure duration; however, the repetitive pulse ED_{50}s were always some factor below the continuous wave ED_{50}s. This correction factor is dependent on the pulse repetition frequency and the duration of each individual pulse in the train. It was applied as a multiplicative correction to the continuous wave maximum permissible exposure to obtain the permissible exposure for repetitive pulse condition. A "margin of safety" comparable to those imposed for continuous wave conditions was obtained. The alternate method applied a multiplicative correction to a single pulse in the train. This correction was dependent only on the number of pulses in the train. Because of the limitations of the present standard, this method was not as consistent in providing an adequate "margin of safety" as the correction factor method; however, the alternate method does suggest that an average pulse repetition frequency can be used for pulse coded trains in the computation of permissible exposures.

It is recommended that the correction factor method be incorporated into the current Army laser protection standards. It is further recommended that the average pulse repetition frequency be used in the calculation of the permissible exposure for repetitive pulse conditions with a variable interpulse spacing.

ABSTRACT

Two methods are described for the calculation of permissible ocular exposure to repetitive pulse laser radiation. The rationale for these methods (the correction factor method and the alternate method) is based upon available experimental data from several laboratories. The ED_{50}s (effective dose for 0.50 probability of an ophthalmoscopically visible retinal lesion) for repetitive pulse exposures expressed in terms of the total intraocular energy are proportional to the pulse train duration to the 3/4 power. The continuous wave ED_{50}s exhibit the same dependence on the exposure duration; however, the repetitive pulse ED_{50}s were always some factor below the the continuous wave ED_{50}s. This correction factor is dependent on the pulse repetition frequency and the duration of each individual pulse in the train. It was applied as a multiplicative correction to the continuous wave maximum permissible exposure to obtain the permissible exposure for repetitive pulse conditions. A "margin of safety" comparable to those imposed for continuous wave conditions was obtained. The alternate method applied a multiplicative correction to a single pulse in the train. This correction was dependent only on the number of pulses in the train. Because of the limitations of the present standard, this method was not as consistent in providing an adequate "margin of safety" as the correction factor method; however, the alternate method does suggest that an average pulse repetition frequency can be used for pulse coded trains in the computation of permissible exposures.

It is recommended that the correction factor method be incorporated into the current Army laser protection standards. It is further recommended that the average pulse repetition frequency be used in the calculation of the permissible exposure for repetitive pulse conditions with a variable interpulse spacing.

PREFACE

The authors wish to thank David H. Sliney of the U.S. Army Environmental Hygiene Agency for several helpful discussions concerning this somewhat esoteric subject. They also wish to acknowledge C. William Van Sice for his willing patience and persistence in the preparation of the many figures and LAIR's Technical Publication Editor, Lottie B. Applewhite, for her special suggestions and assistance.

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INTRODUCTION

Over the past 15 years, dose-response relationships have been obtained for ocular exposure to laser radiation. Most of the research has been conducted on rhesus monkey eyes with the ophthalmoscopic observation of a retinal lesion as the response criterion. The ED_{50}s (effective dose for a 0.50 probability of observing a lesion) have been determined for a minimal retinal irradiance diameter which presumably is the "worst case" viewing situation (i.e. the minimal amount of energy into the eye required to produce a retinal lesion). From these data, the maximum permissible exposures (MPEs) have been derived. Because of the multiplicity of exposure conditions and the complexity of the biological response, the permissible exposure limits must continually be reviewed and revised so that adequate safety margins are assured while no unwarranted limitations are placed on the field deployment of laser devices.

An increasing number of military laser systems operate in a repetitive pulse mode. The present pulse train standard in TB Med 279 (1) was based upon a limited set of early data (2-4). The purpose of this report is to provide detailed arguments based on experimental data from several different laboratories for an alternate approach for the computation of permissible exposure limits for repetitive pulse trains. The evolution of this approach was initiated by the evaluation of recent dose-response data obtained in this laboratory for repetitive pulse neodymium laser radiation (5). The ED_{50}s expressed in terms of the total intraocular energy (TIE) were plotted with respect to the total duration of the pulse train (T). The slope of the line through the data exhibits the same $T^{3/4}$ dependence that the line through the ED_{50}s for continuous wave (cw) neodymium laser radiation

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1. Department of the Army. TB Med 279, 30 May 1975
2. Wolbarsht, M.L., and D.H. Sliney. Chapter 10. In: Laser Applications in Medicine and Biology, Vol 2. M.L. Wolbarsht (ed), 1974
3. Skeen, C.H., et al. Final Report. Technology Inc. June 1972 (AD 746795)
4. Skeen, C.H., et al. Final Report. Technology Inc. June 1972 (AD746793)
5. Lund, D.J., and E.S. Beatrice. Documented, LAIR. Nov 1977

exhibits. When other experimental data were evaluated, a similar dependence of the repetitive pulse data was observed. However, the factor by which the pulsed data was below the continuous wave data was dependent on the pulse repetition frequency and the duration of each individual pulse in the train. This led to the following arguments for the treatment of repetitive pulses by laser safety standards.

CORRECTION FACTOR METHOD

In general, the maximum permissible exposure (MPE) for a given exposure condition has been obtained by dividing the ED_{50} for ophthalmoscopic criterion by a factor S.

$$MPE(T) = \frac{ED_{50}(T)}{S} \qquad 1$$

(The Glossary contains a list of definitions of the symbols and terms used in this report.) This factor S, referred to in this report as the "margin of safety," has a numerical value between 10 and 100 (in most cases) and has been rationalized by different groups in different ways (2). If sufficient data were available, it seems reasonable that repetitive pulse trains could be treated in a similar manner.

$$MPE^{RP}(T) = \frac{ED_{50}^{RP}(T)}{S} \qquad 2$$

Available repetitive pulse data from several laboratories for neodymium laser (1060 nm) and argon laser (514.5 nm) radiation are tabulated in Tables 1 and 2. The $ED_{50}^{RP}(T)$ is expressed as the total intraocular energy (TIE) for the total duration of the pulse train T. The continuous wave $ED_{50}(T)$s are given in Table 3. A correction factor (CF) was obtained by dividing the $ED_{50}^{RP}(T)$ for a pulse train of total duration T (with each individual pulse in the train of duration t) by the $ED_{50}(T)$ for a continuous wave exposure of duration T.

$$CF = \frac{ED_{50}^{RP}(T)}{ED_{50}(T)} \qquad 3$$

By combining equations 1, 2, and 3, this important relationship is obtained.

$$MPE^{RP}(T) = CF\ MPE(T) \qquad 4$$

Therefore the $MPE^{RP}(T)$ can be obtained by multiplying the MPE(T) for a continuous wave exposure of duration T by the correction factor CF.

The correction factors, tabulated in Tables 1 and 2, were plotted as a function of pulse repetition frequency (PRF) for each laser wavelength and individual pulse duration t (Figures 1 and 2) (6-13). For $t > 10\ \mu s$, the correction factors for a given t are proportional to PRF. For $t < 10\ \mu s$, the functional dependence of the lines drawn is the same; however, the data do not follow this dependence as closely.

The numerical relationship between CF(10 μs) and PRF is given in equation 5.

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6. Bresnick, G.H. et al. Invest Ophthalmol 9:901-910,1970
7. Lund, D.J., et al. Memorandum Report M70-24-1. Frankford Arsenal, 1973
8. Lund, D.J. Documented, LAIR. Nov 1977
9. Hemstreet, H.W., et al. Annual Report 1. USAF Contract. Technology Inc, Feb 1974
10. Gibbons, W.D., and D.E. Egbert. USAF Technical Report SAM-TR-74, Feb 1974 (AD 777144/7)
11. Hemstreet, H.W., et al. Second Annual Report. USAF Contract. Technology Inc, Feb 1975
12. Ebbers, R.S., and I.L. Dunsky. Aerospace Med 44: 317-318, 1973
13. Ham, W.T. Final Report to the Army for Period 1 Sep 76 to 31 Aug 77. Medical College of Virginia, 1977.

$$CF(10\ \mu s) = 6.25 \times 10^{-5}\ PRF \qquad 5$$

The ratio of CF(t) to CF(10 μs) is defined as R.

$$R = \frac{CF(t)}{CF(10\ \mu s)} \qquad 6$$

The values of R taken from the series of curves in Figures 1 and 2 were plotted as a function of t (Figure 3), and the numerical relationships between R and t were derived.

For $t > 2\ \mu s$:

$$R = 5.6 \times 10^{4}\ t \qquad 7$$

For $t < 2\ \mu s$:

$$R = 2.9 \times 10^{-7}\ t^{-1} \qquad 8$$

When equations 5, 6, 7, and 8 are combined, the following is obtained:

For $t > 2\ \mu s$:

$$CF(t) = 3.5\ PRF\ t \qquad 9$$

For $t < 2\ \mu s$:

$$CF(t) = 1.8 \times 10^{-11}\ PRF\ t^{-1} \qquad 10$$

For a given set of repetitive pulse exposure conditions, the revised permissible exposure can be obtained by using equations 4, 9, and 10. The continuous wave permissible exposures {MPE(T)} were used as they presently exist in *TB Med 279*.

Permissible Exposures via Correction Factor Method

The correction factor method was used to determine the permissible exposure for repetitive pulse conditions based upon the existing continuous wave standard (1). Both the present permissible exposure for repetitive pulse conditions and those obtained by this method are graphically displayed for easy evaluation (Figures 4-14). A discussion of each figure is given in the legend. The permissible exposures obtained by the correction factor method will be referred to as the "revised $MPE^{RP}(T)$." All doses represented on these plots are total intraocular energy for the total duration of the train T. The total intraocular energy was calculated from the present standard by multiplying the maximum permissible radiant exposure incident on the cornea by the area defined by a 7 mm limiting aperture (maximum pupillary aperture).

The neodymium laser repetitive pulse data (Figures 4-8) all had individual pulse durations (t) less than 2 μs, consequently equation 10 was applied. The calculation of the permissible exposure from the present standard for these conditions required the use of the single pulse correction C_p (1). The current permissible exposures are not parallel to the experimental data and generally impose a lower permissible exposure for the shorter train durations. The revised $MPE^{RP}(T)$s are parallel to the experimental data and offer "margins of safety" that are comparable to those imposed for cw conditions. For some conditions, the revised $MPE^{RP}(T)$ impose lower permissible exposure limits whereas in others the permissible exposures are elevated. Neodymium laser data (PRF = 1000 Hz, t = 180 ns, Figure 5) were available for 2 to 1000 pulses in the train. Note the $T^{3/4}$ dependence of the repetitive pulse data for this wide range of train durations.

The repetitive pulse data for argon laser exposures are shown in Figures 9-12. For t > 10 μs, the permissible radiant exposure $\{MPE^{RP}(T)\}$ for the total duration T of the pulse train is the permissible radiant exposure for the total on time pulse (TOTP), from the present standard (1). The TOTP is the product of the duration of each individual pulse t and the number of pulses n. The number of pulses n is the product of the pulse repetition frequency (PRF) and the total duration of the train T (n = PRF T).

$$TOTP = n\ t = PRF\ T\ t \qquad 11$$

$$MPE^{RP}(T) = MPE(TOTP) \qquad 12$$

For a given wavelength and $10\ \mu s < TOTP < 10\ s$, the following expression is obtained.

$$MPE(TOTP) = k\ (PRF\ T\ t)^{3/4} \qquad 13$$

$$MPE^{RP}(T) = (PRF\ t)^{3/4}\ MPE(T) \qquad 14$$

The factor k is obtained from the standard for the particular wavelength of interest. This is analogous to the correction factor method, however the effective correction factor CF is $(PRF\ t)^{3/4}$ for the present standard rather than 3.5 PRF t (equation 9). This difference is graphically shown in Figures 9-12. In both cases, the permissible exposures follow the $T^{3/4}$ dependence of the experimental data. The only difference is the magnitude of the "margin of safety."

Two additional data sets were evaluated by using the correction factor method. These data sets are important because the exposures conditions are different from those considered so far. The frequency doubled neodymium laser data (14) (Figure 13) at 530 nm are the only repetitive pulse visible wavelength data evaluated where the duration of an individual pulse in the train was less than 10 µs. In this case, the pulse repetition frequency was 5 Hz with t = 15 ns. The second data set (13,15) was obtained for a helium cadmium laser operating at 441.6 nm (Figure 14). The pulse repetition frequency was 1 Hz and the duration of a single pulse in the train was 8 ms with a total train duration of 1000 s. The continuous wave ED_{50}s were also determined for exposure

14. Gibbons, W.D. USAF Technical Report SAM-TR-73-45, Nov 1973 (AD 770561/9)
15. Ham, W.T., et al. Nature 260:153-155, 1976

durations from 1 to 1000 s. The retinal image diameter in both cases was 500 microns. The maximum permissible exposures from the present standard for the "worst case" cw conditions from 1 to 10 s in duration are less than a factor of 3 below the experimental data. If the dependence of the ED_{50} on the retinal image diameter is approximately the same as that obtained by other investigators (16) for longer wavelength radiation and shorter exposure durations, then the present continuous wave maximum permissible exposures are not adequate for these conditions.

Limitations of the Correction Factor Method

Given the empirically derived correction factors in equations 9 and 10, certain limitations must be applied. The value of the correction factor must never exceed 1.0. For $t > 2$ μs (Equation 9), CF will be greater than one if PRF $> (3.5\ t)^{-1}$. From the data considered, this occurred for the 10000 Hz, $t = 40$ μs data. For this case, the $ED_{50}^{RP}(T)$ was comparable to the continuous wave $ED_{50}(T)$ (Figure 10); consequently, a correction factor of 1.0 is appropriate. The larger t becomes, in this case, the lower the required pulse repetition frequency for a unity correction factor (note that the PRF must always be less than t^{-1}). As the pulse repetition becomes smaller for a given t, the correction factor continues to decrease suggesting that a lower limit should be imposed. Hemstreet et al (11) determined the $ED_{50}^{RP}(T)$s for frequencies less than 0.1 Hz (Table 5). For a pulse repetition frequency on the order of 0.1 Hz, the energy per pulse for a repetitive pulse train was comparable to the energy required for a single pulse to produce the "same" effect. Consequently, the effect is produced by the first pulse in the train. Since these data indicate for ophthalmoscopic criteria that there is no additivity or synergism between pulses separated by more than 10 seconds, the single pulse permissible exposures should be applied.

For $t < 2$ μs, CF must be set equal to 1.0 if the PRF is greater than $5.55 \times 10^{10}\ t$. Two sets of experimental data that meet this condition are the gallium arsenide laser data (17) (PRF = 120 kHz, t = 500 ns) and the mode locked

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16. Frisch, G.D., et al. Invest Ophthalmol 10:911-919,1971
17. Lund, D.J., et al. LAIR Report No. 30. Oct 1976

neodymium laser data (PRF = 150 MHz, t = 300 ps). The revised $MPE^{RP}(T)$s offer adequate "margins of safety" in both cases (Figure 15). There are certain conditions where a higher energy per pulse is obtained by using the correction factor method than is permitted for a single pulse. An example of this is when PRF = 1 Hz, t = 10 ns, λ = 1060 nm and where the pulse train contains two pulses (T = 2 s). CF is 1.8×10^{-3} (Equation 10) and the permissible total intraocular energy is 10.1 μJ (i.e. 5.0 μJ/pulse). Consequently, the energy per pulse is higher for two pulses separated by one second than the permissible total intraocular energy for a single exposure (1.9 μJ). If this occurs, the single pulse permissible exposure must be applied.

In summary, for a given set of repetitive pulse exposure conditions, a correction factor (given by equation 9 or 10) is multiplied by the permissible exposure for a continuous wave exposure of duration T. This product is the permissible exposure for the repetitive pulse condition. Three limitations must be imposed on this procedure.

1. If the correction factor exceeds 1.0, then the cw MPE(T) is used.

If: $CF > 1.0$

then: $MPE^{RP}(T) = MPE(T)$

2. If the calculated permissible exposure per pulse obtained with the correction factor method exceeds the permissible exposure for a single pulse of duration t, then the single pulse permissible exposure is the permissible exposure for each pulse in the train.

If: $MPE(t) < CF\ MPE(T)/n$

then: $MPE^{RP}(T) = n\ MPE(t)$

3. If the pulse repetition frequency is less than 0.1 Hz, then the single pulse permissible exposure is the permissible exposure for each pulse in the repetitive train.

If: $PRF < 0.1$ Hz

then: $MPE^{RP}(T) = n\ MPE(t)$

AN ALTERNATE METHOD

Presently, many Army systems operate in pulse coded mode. Determination of the permissible exposure by using the present standard or the correction factor method is confounded because the pulse repetition frequency is not fixed for any given exposure sequence. In addition, little or no bioeffects data exist for the many possible pulse coded exposure conditions. A method of determining the permissible exposure that is independent of the pulse repetition frequency would certainly be advantageous. The following arguments suggest such a method that depends only on the number of pulses in the train. The basis for this method is the important observation that $ED_{50}^{RP}(T)$ exhibits a $T^{3/4}$ dependence. This was also the basis for the development of the correction factor method.

The experimental data for repetitive pulse exposure conditions suggest a $T^{3/4}$ dependence of the $ED_{50}^{RP}(T)$.

$$ED_{50}^{RP}(T) = b\ T^{3/4} \qquad 15$$

The constant b uniquely defines the line for a given set of exposure conditions. Consider all repetitive pulse data $\{ED_{50}^{RP}(T)\}$ where T = 1/PRF. Only one pulse can be obtained in this time interval, consequently the $ED_{50}^{RP}(1/PRF)$ should be equal to or at least proportional to $ED_{50}(t)$, where Q is the constant of proportionality.

$$ED_{50}^{RP}(1/PRF) = Q\ ED_{50}(t) \qquad 16$$

Values for the $ED_{50}^{RP}(1/PRF)$ were determined by extrapolation from the lines through the experimental data and were divided by the single pulse thresholds $\{ED_{50}(t)\}$ to obtain Q. Since the single pulse thresholds $\{ED_{50}(t)\}$ were determined as a precursor to the repetitive pulse thresholds $\{ED_{50}^{RP}(T)\}$, the experimental conditions were essentially the same (i.e., the same retinal irradiation site, same observer, same dosimetry) thus allowing an internally consistent comparison in the determination of Q. These values of Q are given in Table 4

for all data in Tables 1 and 2 and a plot of the average values of Q as a function of the individual pulse duration t is shown in Figure 16. By incorporating equation 16 in equation 15, the equation becomes.

$$ED_{50}^{RP}(T) = n^{3/4}\ Q\ ED_{50}(t) \qquad 17$$

If both sides are divided by S, the following is obtained:

$$MPE^{RP}(T) = n^{3/4}\ Q\ MPE(t) \qquad 18$$

When t is less than 10 μs, the permissible radiant exposure per individual pulse in the train is obtained from the present standard by multiplying the permissible radiant exposure for a single pulse of duration t by a factor C_p. To obtain the total radiant exposure for a pulse train of duration T, the permissible radiant exposure per pulse is multiplied by the number of pulses (n) in the train.

$$MPE^{RP}(T) = n\ C_p\ MPE(t) \qquad 19$$

The effective C_p obtained for all values of t can be obtained from equations 18 and 19.

$$C_p = Q\ n^{-1/4} \qquad 20$$

An expression for C_p can be obtained from the present standard for t > 10 μs by using the definition of C_p in equation 19 and the $MPE^{RP}(T)$ given in equation 12.

$$C_p = \frac{MPE(TOTP)}{n\ MPE(t)} \qquad 21$$

For a given wavelength, the ratio {MPE(TOTP)/MPE(t)} is equal to the ratio of the arguments to the 3/4 power $\{(TOTP/t)^{3/4}\}$ provided that t and TOTP are not greater than 10 seconds.

$$C_p = \frac{(TOTP)^{3/4}}{n\ t^{3/4}} \qquad 22$$

Consequently, the present standard for t > 10 μs uses a value of 1.0 for Q.

The range of values of Q from all data (Table 5) is from 0.2 to 3.4. Let Q = 1.0 for all values of t (i.e. $C_p = n^{-1/4}$). For convenience this method will be referred to as the $C_p = n^{-1/4}$ method for determining permissible exposures. A comparison of the current C_p and $C_p = n^{-1/4}$ is shown in Figure 17. The permissible exposure for a repetitive pulse train of duration T is obtained from equation 18.

$$MPE^{RP}(T) = n^{3/4}\ MPE(t) \qquad 23$$

The permissible exposures by this method are also shown on Figures 4-14. For t > 10 μs, the permissible exposures are the same as the present standard (equation 23). For t < 10μs, the effective permissible exposures (Figures 4-8) in some cases do not offer a consistent "margin of safety". In all cases the $T^{3/4}$ dependence of the permissible exposure is preserved. One of the reasons the "margins of safety" are not consistent for t < 10 μs is the fact that the current MPE(t) is a constant, whereas the $ED_{50}(t)$ increases as t becomes smaller for 10 ns < t < 10 μs (Table 4). The assumption that the permissible exposure is some constant factor below the ED_{50} for ophthalmoscopic criteria is not included in the present standard for t < 10 μs. Unless the current standard is changed to include this dependence, this method ($C_p = n^{-1/4}$) of computing the permissible exposures will remain less consistent in providing an adequate "margin of safety" than the correction factor method or the method used by the present standard. The variability of the values of Q also contributes to the inconsistency. Certainly more experimental data is required for these exposure conditions.

The $C_p = n^{-1/4}$ method is based upon the experimental data. The permissible exposure calculated by this method for repetitive pulse trains is independent of the pulse repetition frequency and, therefore, is equally applicable to pulse trains with variable interpulse spacings. In the present dilemma concerning the application of the present standard to pulse coded conditions, this evaluation does suggest that an average pulse repetition frequency would be appropriate for the calculation of the permissible exposure.

DISCUSSION

Experimental data from many investigators were used in these evaluations. The range of physical parameters is given below:

$$10 \text{ ns} \leqslant t \leqslant 8 \text{ ms}$$

$$2 \text{ ms} \leqslant T \leqslant 1000 \text{ s}$$

$$1 \text{ Hz} \leqslant \text{PRF} \leqslant 10000 \text{ Hz}$$

$$441.6 \leqslant \lambda \leqslant 1060 \text{ nm}$$

The biological measure used as the basis for comparison was the observation of a retinal lesion 50% of the time at one hour (or twenty-four hours for exposure durations greater than 30 seconds) after the exposure. Certainly one can argue that the retinal response is not the same for these extremes of exposure conditions; however, the comparisons were made for the same wavelength and total duration of the exposure. The retinal exposure site for some of the experimentally determined ED_{50}s was the macula, whereas other investigators based their statistics on paramacular exposures. Other experimental conditions introduce possible errors in these comparisons. These include the corneal irradiance diameter (16), observation of the fundus, measurement of physical quantities (dose, beam divergence), the refractive state of the eye, and the actual retinal irradiance diameter. In general, most of the experimental procedures and techniques are similar, however the task of separating the differences is difficult if not impossible. Regardless of these differences, the revised permissible exposures obtained by using the correction factor method for repetitive pulse conditions provide "margins of safety" comparable to those provided for

continuous wave exposures based on the same biological response criterion.

SUMMARY AND CONCLUSIONS

Two methods are described to calculate the permissible exposure for repetitive pulse conditions. The rationale for these methods is based upon the available experimental data. Both methods require the use of the current permissible exposure for single exposures of a given duration. The correction factor method applies a multiplicative correction to the continuous wave MPE(T), whereas the $C_p = n^{-1/4}$ method applies a correction of $n^{-1/4}$ to the MPE(t). The difference between the revised permissible exposures and the current standard for repetitive pulses depends upon the exposure conditions. The revised permissible exposures are higher than the current values for some conditions and lower for others. The $C_D = n^{-1/4}$ method is not as consistent in providing an adequate "margin of safety" because of the limitations imposed by the existing standard. The $C_p = n^{-1/4}$ method does suggest that an average pulse repetition frequency can be used for pulse coded trains for the computation of permissible exposures with the correction factor method or the current standard. More bioeffects research is required to substantiate this observation.

RECOMMENDATIONS

As a result of this review and analysis of available repetitive pulse data, it is recommended that the correction factor method be incorporated in the current Army laser protection standard. This method, with the limitations described, provides a consistent "margin of safety" for the exposure conditions where experimental data are available. It is recommended that the average pulse repetition frequency be used in the calculation of the permissible exposure for repetitive pulse conditions with a variable interpulse spacing.

The recommendation of change in permissible exposure limits requires careful consideration and judgement. Laser protection standards have regretfully become more cumbersome and

complex with each revision. As new lasers and exposure conditions are developed, the biological effects and safe exposure limits must be determined. These standards must not be too restrictive or the practical use of such devices may be unjustly prohibited. The protection and safety of personnel exposed to these devices must also be assured. The acute as well as the chronic effects must be ascertained and built into permissible exposure limits.

ADDENDUM

Two documents (Hemstreet et al and Connolly et al, April 1978) concerning the ocular effects of repetitive pulse laser radiation were received after the body of our report was completed. Most of the repetitive pulse data contained in these documents were also in our References 9 and 11. Some additional experimental data as well as descriptions of experimental techniques and a discussion of interpolation methods did appear in the new reports.

Two additional data points were available for repetitive pulse argon laser exposure at 514.5 nm with a train duration of 500 ms (Connolly et al). The duration of each individual pulse in the train was 1 ms. The $ED_{50}^{RP}(T)$s were 94.5 and 750 μJ for pulse repetition frequencies of 10 and 100 Hz respectively. These data are now included in our Figure 12.

We have added an explanation about the data tabulated in Table 5 of our report. These data were taken from Figure 14 (page 41) of Reference 11. Connolly et al (1978) clarify the genesis of these data, some of which were generated by interpolation methods. Although Table 5 in our report shows a comparison of the 'margins of safety' provided by the correction factor method and the current standard, the major conclusion drawn from these data concerned the limitation on the magnitude of the pulse repetition frequency for the application of the correction factor method. Repetitive pulse data and interpolated data (Hemstreet et al) were presented for low pulse repetition frequencies with 2 and 5 pulses in the train for neodymium laser radiation (t = 300 ns, 'nominal'). These results support the application of the single pulse permissible exposure for pulse repetition frequencies less than 0.1 Hz for these exposure conditions (ie. $t \lessdot 2\ \mu s$). Although interpolated data were used, the limitation of the correction factor method is applicable as stated in our report.

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Connolly, J.S., H.W. Hemstreet, and D.E. Egbert. Ocular Hazards of Picosecond and Repetitive-Pulsed Lasers. Volume II: Argon-Ion Laser (514.5 nm). USAF Technical Report SAM-TR-78-21. Brooks Air Force Base, TX: School of Aerospace Medicine, April 1978.

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APPENDIX A

FIGURE 1: Correction Factors for t > 10 μsec

The correction factors CF as a function of pulse repetition frequency for t > 10 μsec.

1:	●	Argon laser data, t = 10 μsec.	Hemstreet et al (11)
2:	□	Argon laser data, t = 40 μsec.	Hemstreet et al (11)
3:	▲	Argon laser data, t = 100 μsec.	Hemstreet et al (11)
4:	■	Argon laser data, t = 1000 μsec.	Hemstreet et al (11)
5:	▽	HeCd laser data, t = 8000 μsec.	Ham (13)

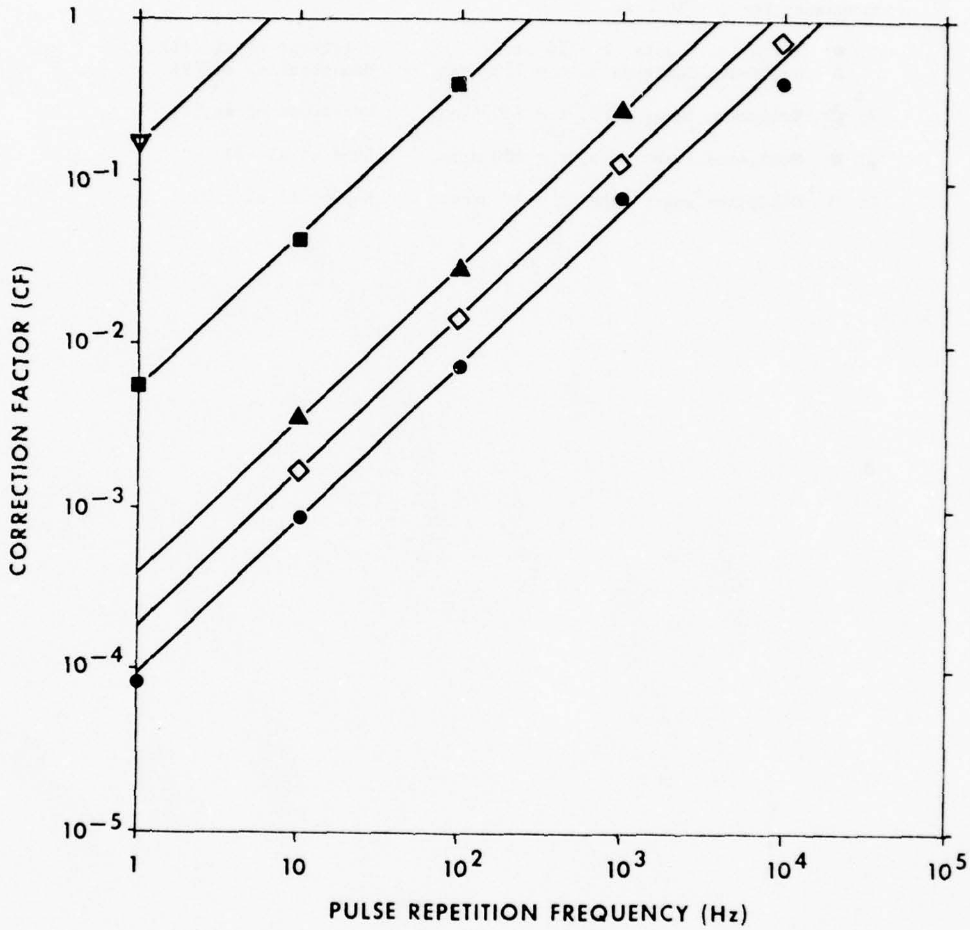
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
CORRECTION FACTOR (CF)
1
10
10^2
10^3
10^4
10^5
PULSE REPETITION FREQUENCY (Hz)

Figure 1

FIGURE 2: Correction Factors for t < 10 μsec

The correction factors CF *as a function of the pulse repetition* frequency for t < 10 μsec.

1:	●	Argon laser data, t = 10 μsec.	Hemstreet et al (11)
	△	Neodymium laser data, t = 270 nsec.	Hemstreet et al (9)
2:	☆	Neodymium laser data, t = 730 nsec.	Hemstreet et at (9)
3:	■	Neodymium laser data, t = 180 nsec.	Lund et al (5)
4:	○	Neodymium laser data, t = 10 nsec.	Ebbers et al (12)

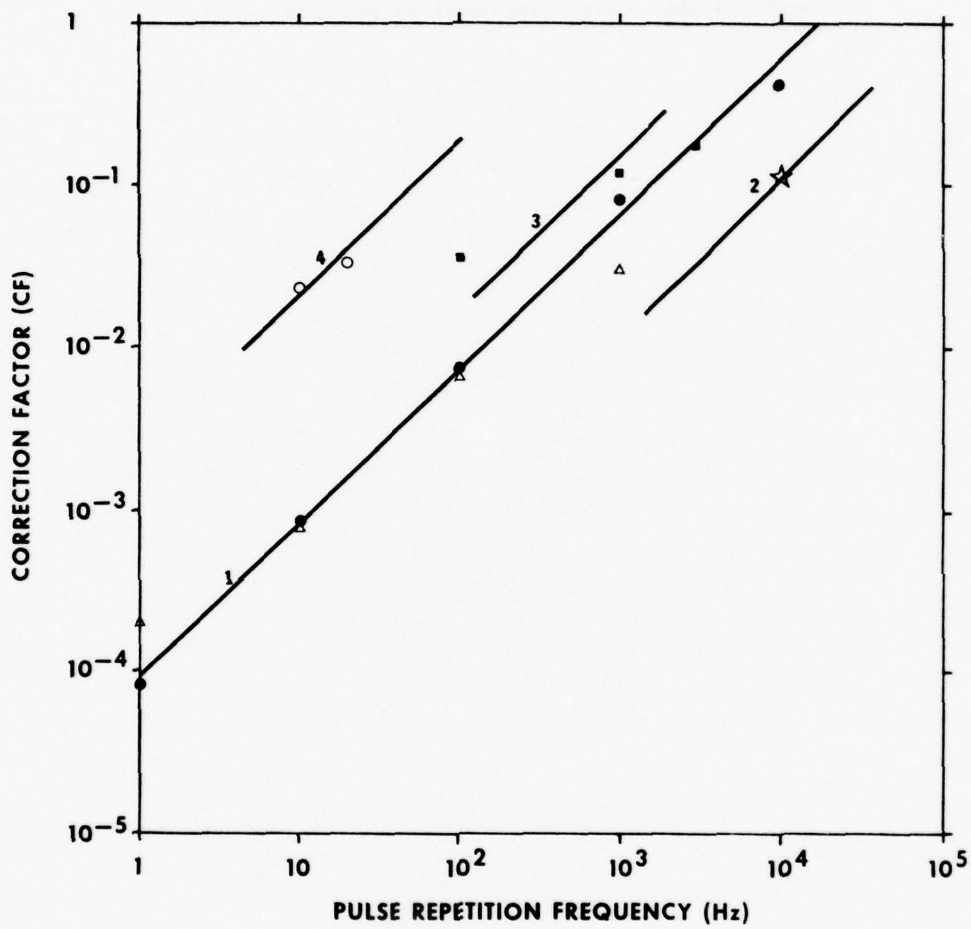
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
CORRECTION FACTOR (CF)
1
10
10^2
10^3
10^4
10^5
PULSE REPETITION FREQUENCY (Hz)
1
2
3
4

Figure 2

FIGURE 3: R as a function of t

R is the ratio CF(t)/CF(10 μsec) where t is the duration of each individual pulse in the repetitive pulse train.

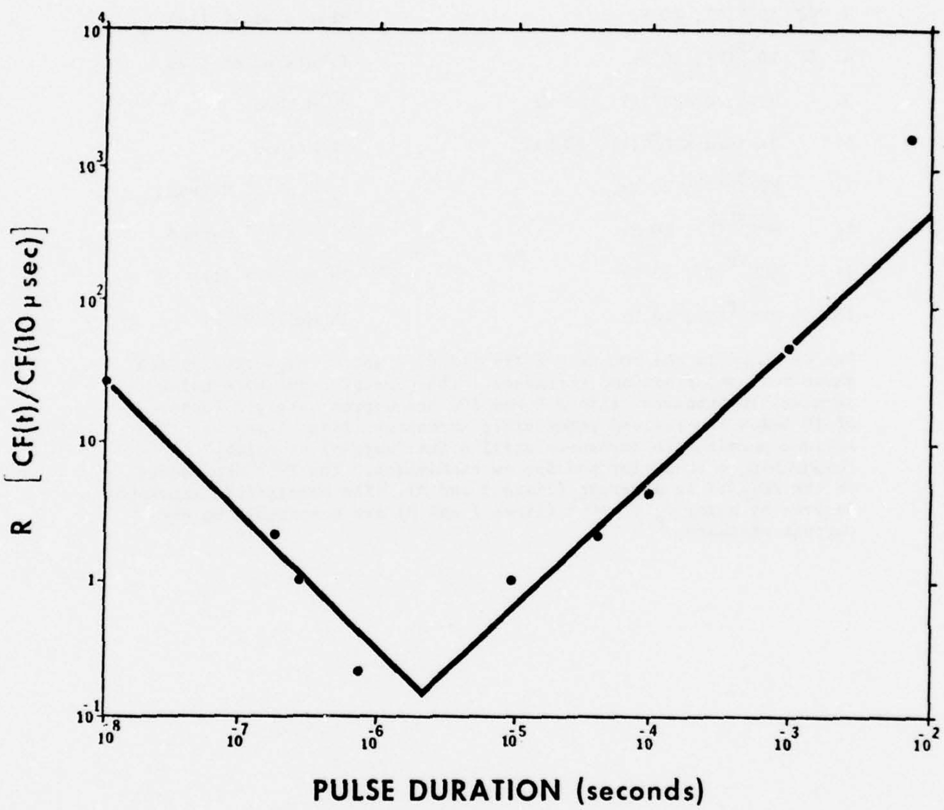

Figure 3

FIGURE 4: Neodymium Laser Repetitive Pulse Data
(PRF = 10 and 20 Hz, t = 10 nsec, λ = 1060 nm)

1:	●	$ED_{50}(T)$	Lund et al (7,8)
2:		$MPE(T)$	TB Med 279 (1)
3:	☆	$ED_{50}^{RP}(T)$, 20 Hz	Ebbers et al (12)
4:	□	$ED_{50}^{RP}(T)$, 10 Hz	Ebbers et al (12)
5:		Revised $MPE^{RP}(T)$, 20 Hz	CF Method
6:		Revised $MPE^{RP}(T)$, 10 Hz	CF Method
7:		$MPE^{RP}(T)$, 20 Hz	$C_p = n^{-1/4}$ Method
8:		$MPE^{RP}(T)$, 10 Hz	$C_p = n^{-1/4}$ Method
9:		$MPE^{RP}(T)$, 20 Hz	TB Med 279 (1)
10:		$MPE^{RP}(T)$, 10 Hz	TB Med 279 (1)

The cw $ED_{50}(T)$s and the cw $MPE(T)$s (lines 1 and 2 respectively) are shown for comparison and reference. The current repetitive pulse permissible exposures (lines 9 and 10) are approximately a factor of 10 below the revised permissible exposures (lines 5 and 6). The revised permissible exposures still offer "margins of safety" comparable to those *imposed for cw* conditions. The $T^{3/4}$ dependence of the $ED_{50}^{RP}(T)$ is apparent (lines 3 and 4). The permissible exposures derived by using $C_p = n^{-1/4}$ (lines 7 and 8) are comparable to the current standard.

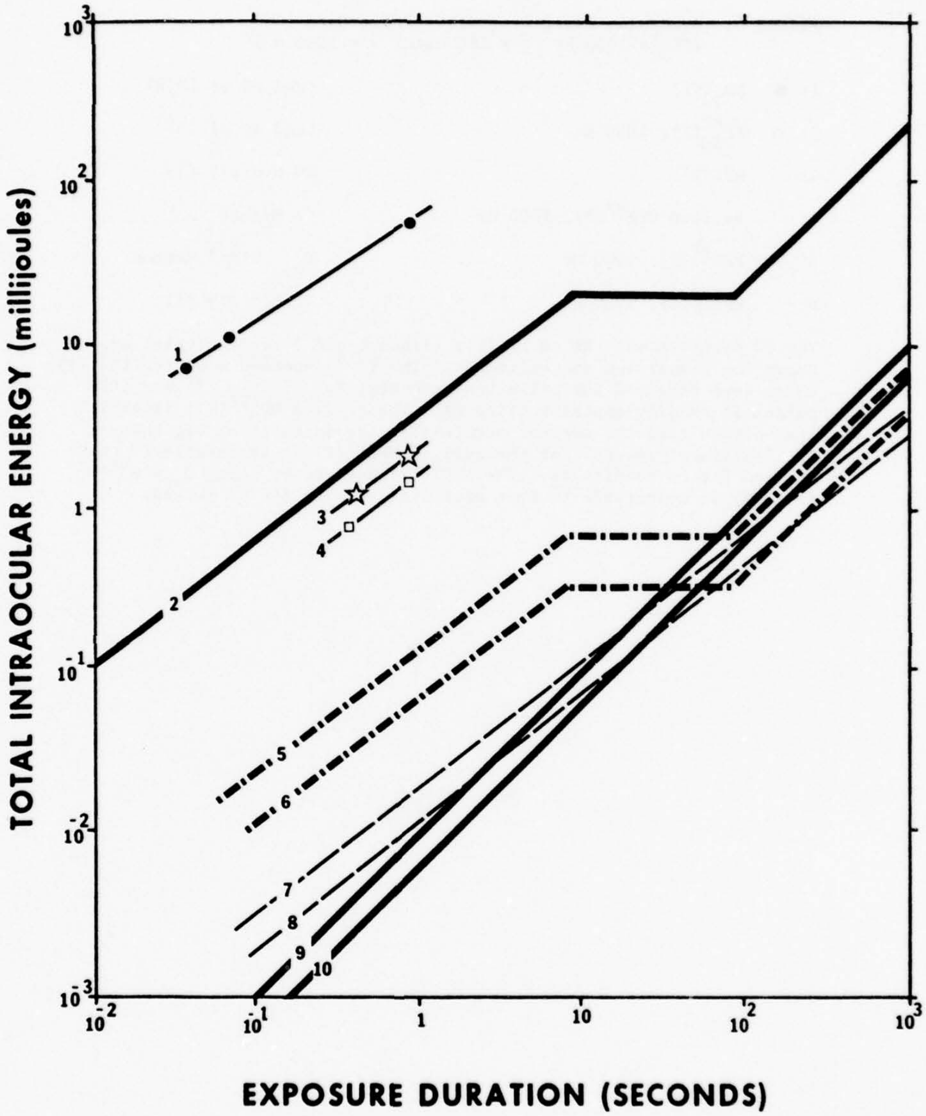
TOTAL INTRAOCULAR ENERGY (millijoules)
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
1
2
3
4
5
6
7
8
9
10
10^{-2}
10^{-1}
1
10
10^2
10^3
EXPOSURE DURATION (SECONDS)

Figure 4

FIGURE 5: Neodymium Laser Repetitive Pulse Data
(PRF = 1000 Hz, t = 180 nsec, λ = 1060 nm)

1:	●	$ED_{50}(T)$	Lund et al (7,8)
2:	Δ	$ED_{50}^{RP}(T)$, 1000 Hz	Lund et al (5)
3:		MPE(T)	TB Med 279 (1)
4:		Revised $MPE^{RP}(T)$, 1000 Hz	CF Method
5:		$MPE^{RP}(T)$, 1000 Hz	$C_p = n^{-1/4}$ Method
6:		$MPE^{RP}(T)$, 1000 Hz	TB Med 279 (1)

The cw $ED_{50}(T)$s and the cw MPE(T)s (lines 1 and 3 respectively) are shown for comparison and reference. The $T^{3/4}$ dependence of the $ED_{50}^{RP}(T)$s which were obtained for pulse trains containing 2, 3, 6, 74 and 1000 pulses is readily apparent (line 2). The revised $MPE^{RP}(T)$s (line 4) are higher than the current permissible exposures (line 6), however the "margin of safety" for the revised $MPE^{RP}(T)$ is comparable to that imposed for cw conditions. The $MPE^{RP}(T)$ derived by using $C_p = n^{-1/4}$ (line 5) is comparable to that obtained by using the CF method.

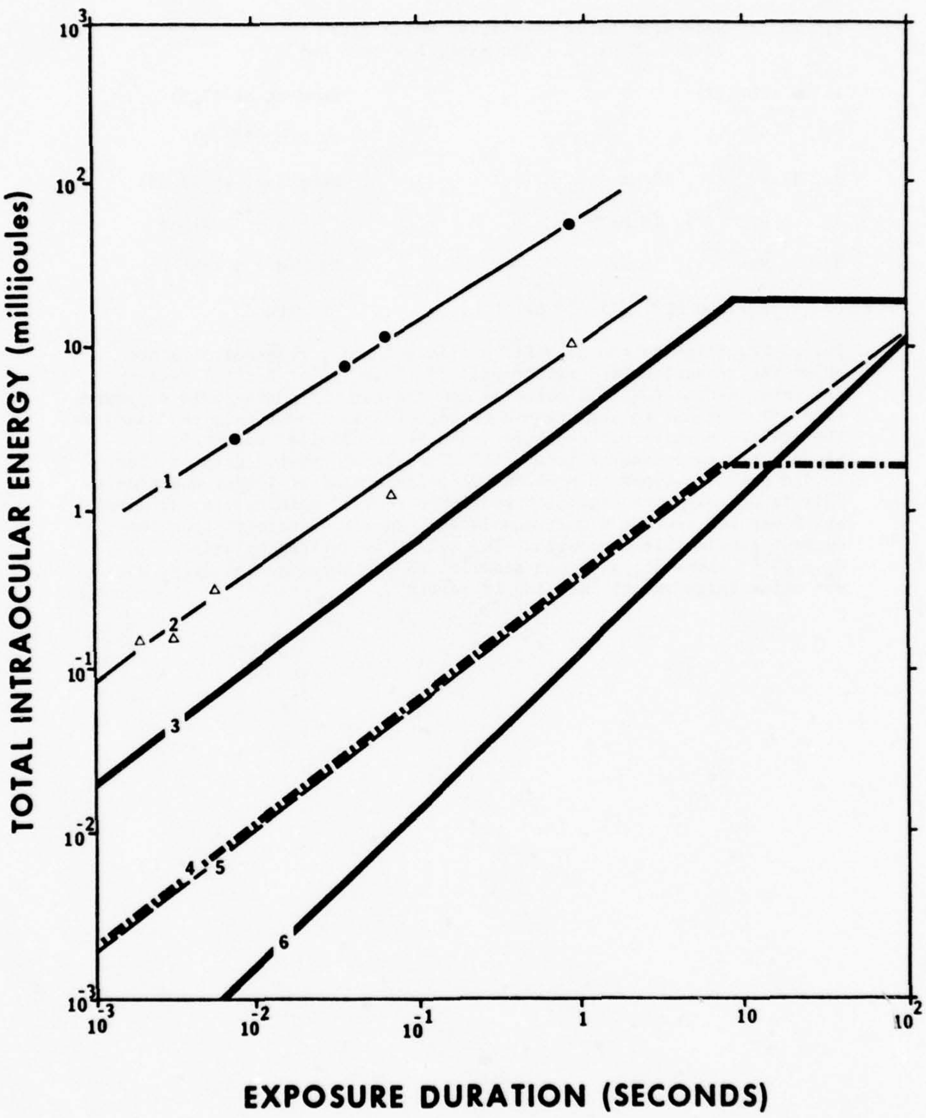
TOTAL INTRAOCULAR ENERGY (millijoules)
10^3
10^2
10
1
10^-1
10^-2
10^-3
1
2
3
4
5
6
10^-3
10^-2
10^-1
1
10
10^2
EXPOSURE DURATION (SECONDS)

Figure 5

FIGURE 6: Neodymium Laser Repetitive Pulse Data
($PRF = 10$ Hz, $t = 270$ nsec, $\lambda = 1060$ nm)

1: ●	$ED_{50}(T)$	Lund et al (7,8)
2:	$MPE(T)$	TB Med 279 (1)
3: □	$ED_{50}^{RP}(T)$, 10 Hz	Hemstreet et al (9)
4:	$MPE^{RP}(T)$, 10 Hz	$C_p = n^{-1/4}$ Method
5:	$MPE^{RP}(T)$, 10 Hz	TB Med 279 (1)
6:	Revised $MPE^{RP}(T)$, 10 Hz	CF Method

The cw $ED_{50}(T)$s and the cw $MPE(T)$s (lines 1 and 2 respectively) are shown for comparison and reference. The "margins of safety" between the experimental $ED_{50}^{RP}(T)$s (line 3) and the current permissible exposures (line 5) decrease to less than a factor of 5 as T increases to 5 seconds. The revised permissible exposure (line 6) is parallel to the line through the experimental data with a "margin of safety" greater than 10 and poses no apparent problem for pulse trains of longer duration. This is one exposure condition where the revised permissible exposures are lower and provide a more consistent "margin of safety" than the current permissible exposures. The $MPE^{RP}(T)$s derived by using $C_p = n^{-1/4}$ (line 4), although parallel to the experimental data, do not offer large enough "margins of safety".

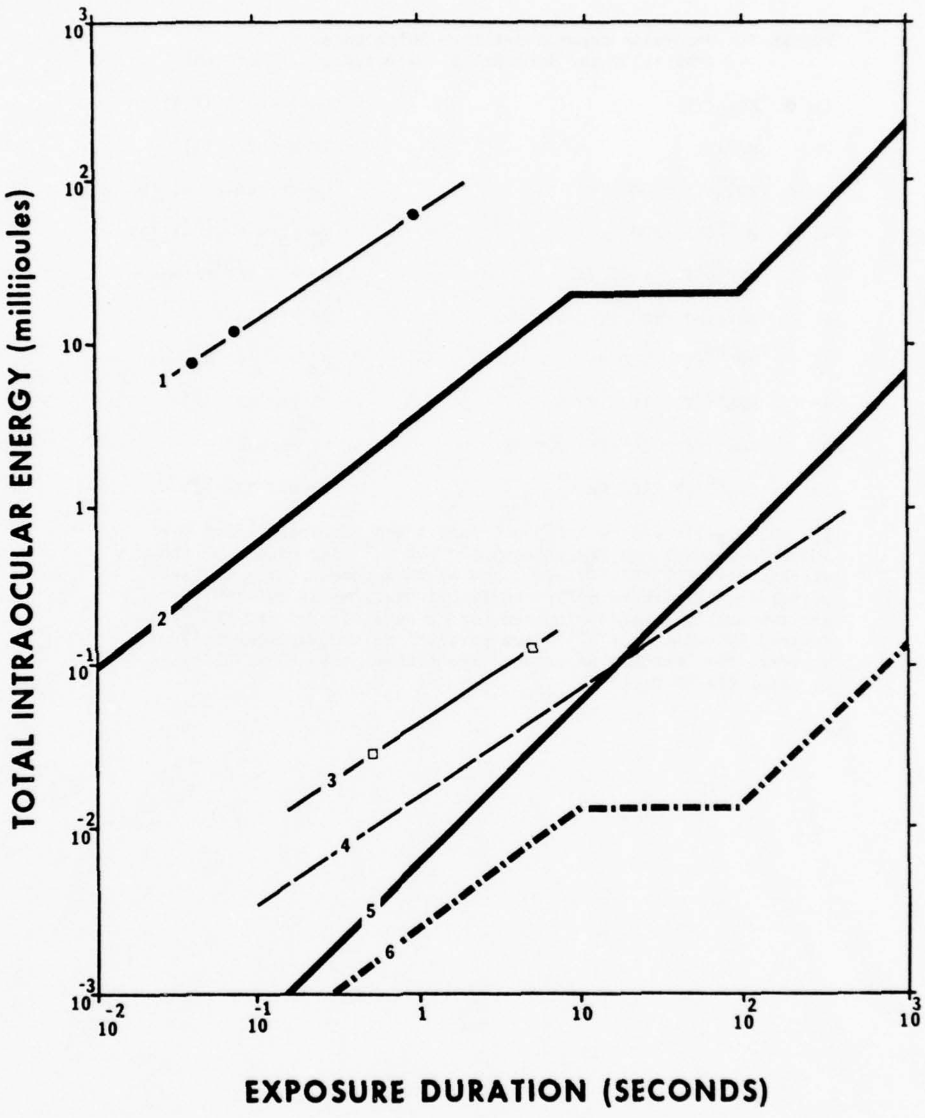
TOTAL INTRAOCULAR ENERGY (millijoules)
EXPOSURE DURATION (SECONDS)
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1
10
10^2
10^3
1
2
3
4
5
6

Figure 6

FIGURE 7: Neodymium Laser Repetitive Pulse Data
(PRF = 100 and 1000 Hz, t = 270 nsec, λ = 1060 nm)

1;	●	$ED_{50}(T)$	Lund et al (7,8)
2:		MPE(T)	TB Med 279 (1)
3:	△	$ED_{50}^{RP}(T)$, 1000 Hz	Hemstreet et al (9)
4:	▲	$ED_{50}^{RP}(T)$, 100 Hz	Hemstreet et al (9)
5:		$MPE^{RP}(T)$, 1000 Hz	$C_p = n^{-1/4}$ Method
6:		Revised $MPE^{RP}(T)$, 1000 Hz	CF Method
7:		$MPE^{RP}(T)$, 100 Hz	$C_p = n^{-1/4}$ Method
8:		$MPE^{RP}(T)$, 1000 Hz	TB Med 279 (1)
9:		Revised $MPE^{RP}(T)$, 100 Hz	CF Method
10:		$MPE^{RP}(T)$, 100 Hz	TB Med 279 (1)

The cw $ED_{50}(T)$s and cw MPE(T)s (lines 1 and 2 respectively) are shown for comparison and reference. The $T^{3/4}$ dependence of the experimental $ED_{50}^{RP}(T)$s (lines 3 and 4) is apparent. The revised permissible exposures offer consistent "margins of safety" that are comparable to those imposed for cw conditions. The $MPE^{RP}(T)$s derived by using $C_p = n^{-1/4}$ are parallel to the experimental data; however, the "margins of safety" are smaller than those obtained by using the CF Method.

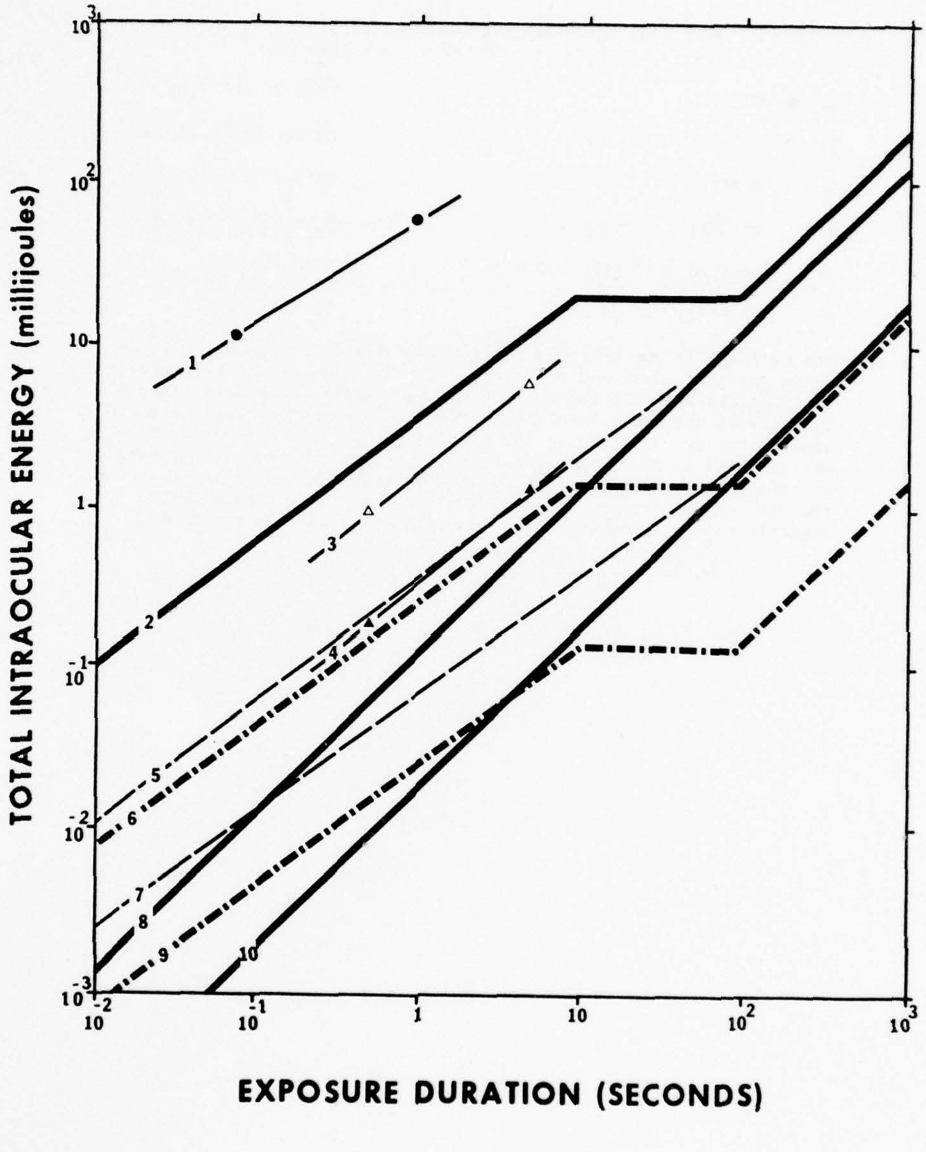
TOTAL INTRAOCULAR ENERGY (millijoules)
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
EXPOSURE DURATION (SECONDS)
10^{-2}
10^{-1}
1
10
10^2
10^3
1
2
3
4
5
6
7
8
9
10

Figure 7

FIGURE 8: Neodymium Laser Repetitive Pulse Data
(PRF = 10000 Hz, t = 730 nsec, λ = 1060 nm)

1:	●	$ED_{50}(T)$	Lund et al (7,8)
2:	○	$ED^{RP}_{50}(T)$, 10000 Hz	Hemstreet et al (9)
3:		MPE(T)	TB Med 279 (1)
4:		$MPE^{RP}(T)$, 10000 Hz	$C_p = n^{-1/4}$ Method
5:		Revised $MPE^{RP}(T)$, 10000 Hz	CF Method
6:		$MPE^{RP}(T)$, 10000 Hz	TB Med 279 (1)

The cw $ED_{50}(T)$s and the cw MPE(T)s (lines 1 and 3 respectively) are shown for comparison and reference. The "margins of safety" between the $ED^{RP}_{50}(T)$s (line 2) and the current permissible exposures (line 6) decrease as the train length increases and are not as large as those imposed for cw conditions. The revised permissible exposures (line 5) are parallel to the line through the experimental data with a "margin of safety" of approximately 7 for train durations less than 10 seconds. The $MPE^{RP}(T)$ derived by using $C_p = n^{-1/4}$ (line 4) are parallel to the experimental data; however, the "margin of safety" is too small.

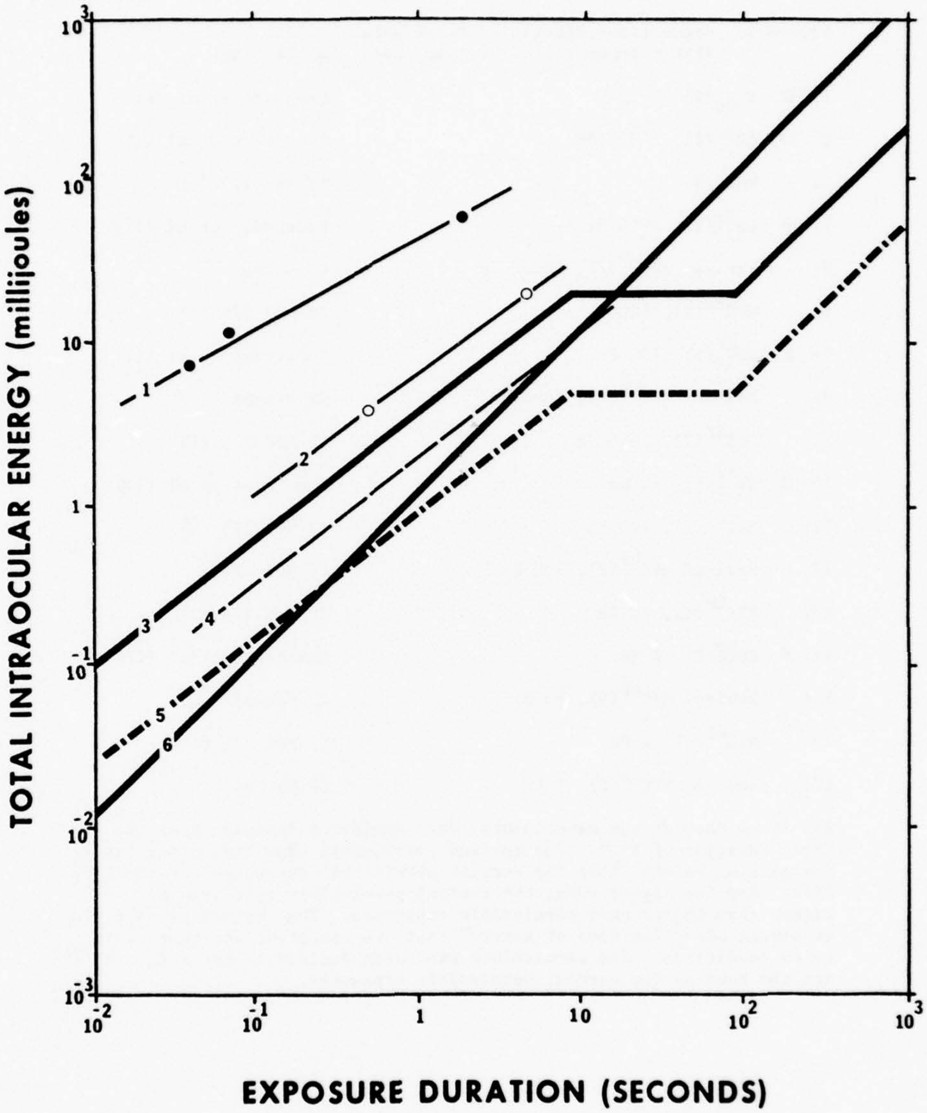
TOTAL INTRAOCULAR ENERGY (millijoules)
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
1
2
3
4
5
6
10^{-2}
10^{-1}
1
10
10^2
10^3
EXPOSURE DURATION (SECONDS)

Figure 8

FIGURE 9: Argon Laser Repetitive Pulse Data
(PRF = 10000 - 1 Hz, t = 10 usec, λ = 514.5 nm)

1:	●	$ED_{50}(T)$	Bresnick et al (6)
2:	○	$ED_{50}^{RP}(T)$, 10000 Hz	Hemstreet et al (11)
3:		MPE(T)	TB Med 279 (1)
4:	△	$ED_{50}^{RP}(T)$, 1000 Hz	Hemstreet et al (11)
5:		Revised $MPE^{RP}(T)$, 10000 Hz	CF Method
6:		$MPE^{RP}(T)$, 10000 Hz	TB Med 279 (1)
7:	▲	$ED_{50}^{RP}(T)$, 100 Hz	Hemstreet et al (11)
8:		Revised $MPE^{RP}(T)$, 1000 Hz	CF Method
9:		$MPE^{RP}(T)$, 1000 Hz	TB Med 279 (1)
10:	□	$ED_{50}^{RP}(T)$, 10 Hz	Hemstreet et al (11)
11:		$MPE^{RP}(T)$, 100 Hz	TB Med 279 (1)
12:		Revised $MPE^{RP}(T)$, 100 Hz	CF Method
13:		$MPE^{RP}(T)$, 10 Hz	TB Med 279 (1)
14:	■	$ED_{50}^{RP}(T)$, 1 Hz	Hemstreet et al (11)
15:		Revised $MPE^{RP}(T)$, 10 Hz	CF Method
16:		$MPE^{RP}(T)$, 1 Hz	TB Med 279 (1)
17:		Revised $MPE^{RP}(T)$, 1 Hz	CF Method

The lines through the experimental data exhibit a dependence on the train duration of $T^{3/4}$. The revised permissible exposures offer larger "margins of safety" than the current permissible exposures for the lower PRFs. For the higher PRFs, the revised permissible exposures are higher than the current permissible exposures. The revised permissible exposures offer "margins of safety" that are consitent and comparable to cw conditions. The permissible exposures derived by using $C_P = n^{-1/4}$ are the same as the current permissible exposures.

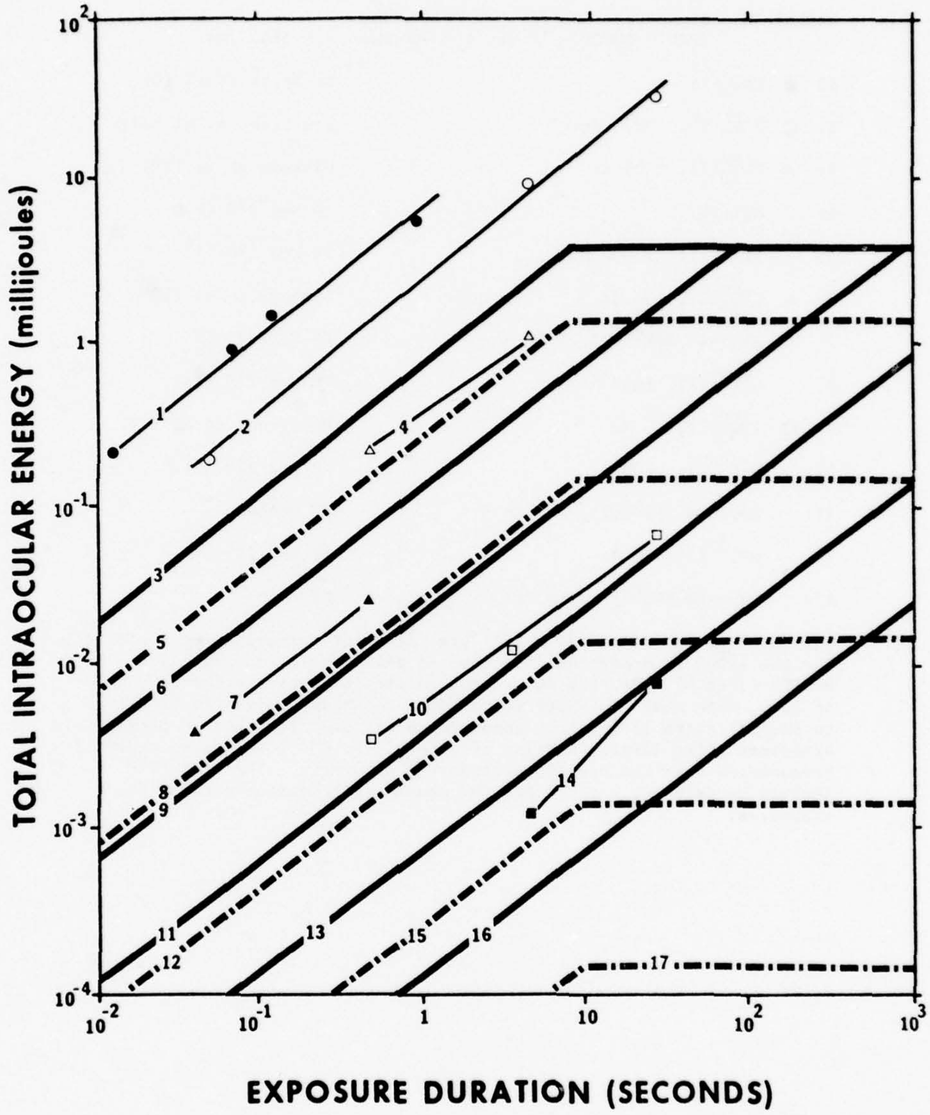
TOTAL INTRAOCULAR ENERGY (millijoules)
EXPOSURE DURATION (SECONDS)
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-2}
10^{-1}
1
10
10^2
10^3
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17

Figure 9

FIGURE 10: Argon Laser Repetitive Pulse Data
(PRF = 10000 - 10 Hz, t = 40 μsec, λ = 514.5 nm)

1:	●	$ED_{50}(T)$	Bresnick et al (6)
2:	○	$ED_{50}^{RP}(T)$, 10000 Hz	Hemstreet et al (11)
3:	△	$ED_{50}^{RP}(T)$, 1000 Hz	Gibbons et al (10)
4:		MPE(T)	TB Med 279 (1)
5:		$MPE^{RP}(T)$, 10000 Hz	TB Med 279 (1)
6:	▲	$ED_{50}^{RP}(T)$, 100 Hz	Gibbons et al (10)
7:		Revised $MPE^{RP}(T)$, 1000 Hz	CF Method
8:		$MPE^{RP}(T)$, 1000 Hz	TB Med 279 (1)
9:	□	$ED_{50}^{RP}(T)$, 10 Hz	Hemstreet et al (11)
10:		$MPE^{RP}(T)$, 100 Hz	TB Med 279 (1)
11:		Revised $MPE^{RP}(T)$, 100 Hz	CF Method
12:		$MPE^{RP}(T)$, 10 Hz	TB Med 279 (1)
13:		Revised $MPE^{RP}(T)$, 10 Hz	CF Method

The cw $ED_{50}(T)$s and the cw MPE(T) are shown for comparison and reference. For the 10000 Hz condition, the revised permissible exposure is the cw MPE(T) (line 4) since the calculated correction factor exceeded a value of 1.0. Note that the experimental data point is comparable to the cw $ED_{50}(T)$ (line 1) for that exposure condition. The revised permissible exposures offer larger "margins of safety" for the lower pulse repetition frequencies than the current permissible exposures. The $MPE^{RP}(T)$s derived by using $C_p = n^{-1/4}$ are the same as the current permissible exposures.

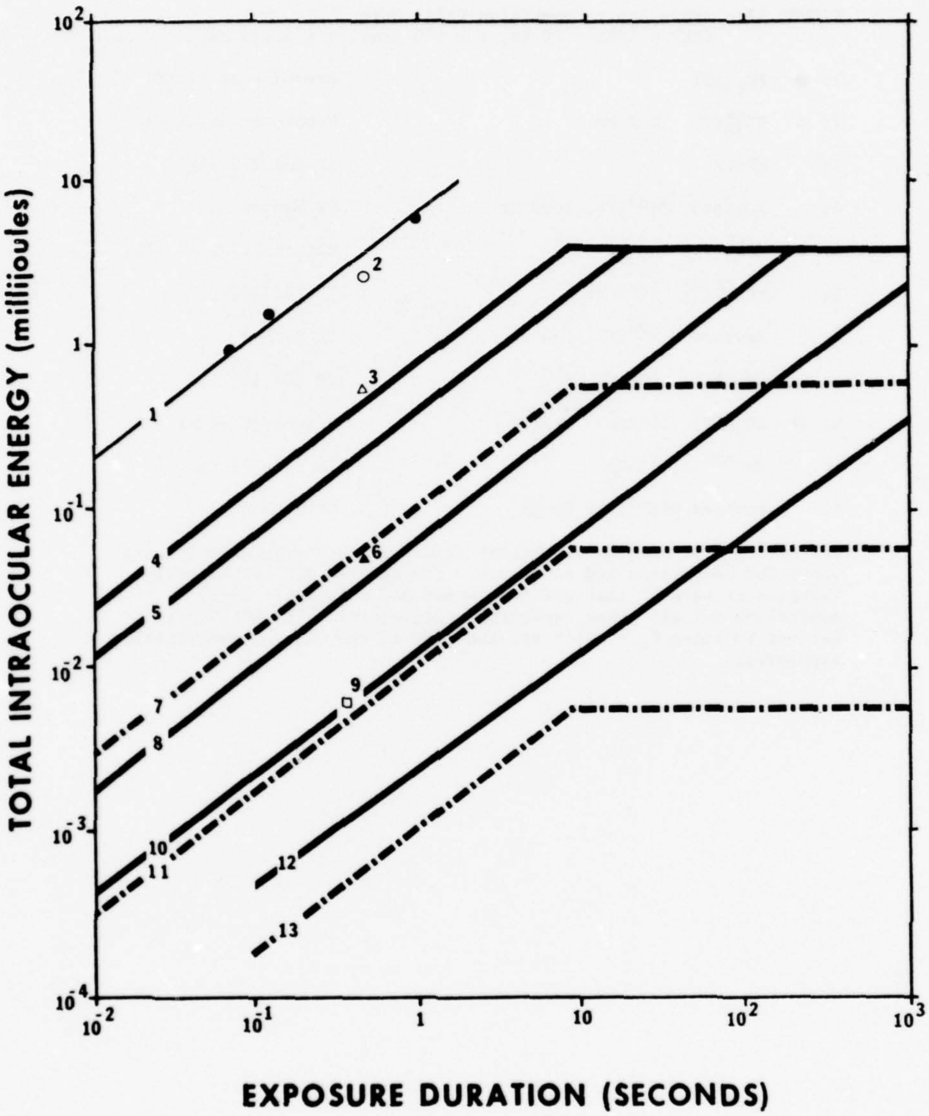
TOTAL INTRAOCULAR ENERGY (millijoules)
EXPOSURE DURATION (SECONDS)
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-2}
10^{-1}
1
10
10^2
10^3
1
2
3
4
5
6
7
8
9
10
11
12
13

Figure 10

FIGURE 11: Argon Laser Repetitive Pulse Data
(PRF = 1000 - 10 Hz, t = 100 μsec, λ = 514.5 nm)

1:	●	$ED_{50}(T)$	Bresnick et al (6)
2:	△	$ED^{RP}_{50}(T)$, 1000 Hz	Hemstreet et al (11)
3:		$MPE(T)$	TB Med 279 (1)
4:		Revised $MPE^{RP}(T)$, 1000 Hz	CF Method
5:	▲	$ED^{RP}_{50}(T)$, 100 Hz	Hemstreet et al (11)
6:		$MPE^{RP}(T)$, 1000 Hz	TB Med 279 (1)
7:		Revised $MPE^{RP}(T)$, 100 Hz	CF Method
8:		$MPE^{RP}(T)$, 100 Hz	TB Med 279 (1)
9:	□	$ED^{RP}_{50}(T)$, 10 Hz	Hemstreet et al (11)
10:		$MPE^{RP}(T)$, 10 Hz	TB Med 279 (1)
11:		Revised $MPE^{RP}(T)$, 10 Hz	CF Method

The cw $ED_{50}(T)$s and the cw $MPE(T)$s (lines 1 and 3 respectively) are shown for comparison and reference. The revised $MPE^{RP}(T)$s provide "margins of safety" that are consistent and comparable to cw conditions for all pulse repetition frequencies. The $MPE^{RP}(T)$s derived by using $C_p = n^{-1/4}$ are the same as the current permissible exposures.

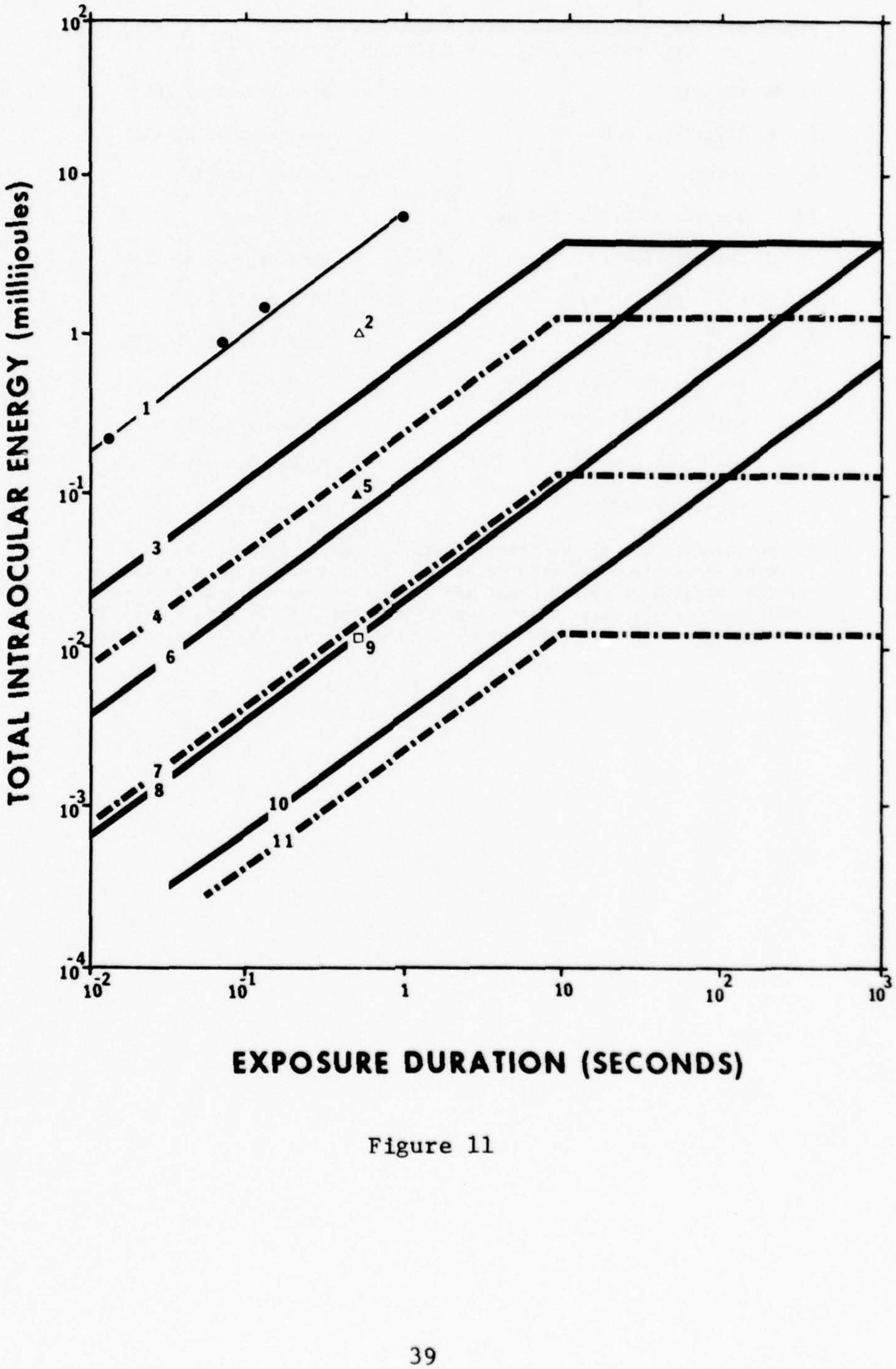
TOTAL INTRAOCULAR ENERGY (millijoules)
EXPOSURE DURATION (SECONDS)
10^{2}
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
1
2
3
4
5
6
7
8
9
10
11

Figure 11

FIGURE 12: Argon Laser Repetitive Pulse Data
(PRF = 100 - 1 Hz, t = 1000 usec, λ = 514.5 nm)

1:	●	$ED_{50}(T)$	Bresnick et al (6)
2:	▲	$ED^{RP}_{50}(T)$, 100 Hz	Hemstreet et al (11)
3:		MPE(T)	TB Med 279 (1)
4:		Revised $MPE^{RP}(T)$, 100 Hz	CF Method
5:	□	$ED^{RP}_{50}(T)$, 10 Hz	Hemstreet et al (11)
6:		$MPE^{RP}(T)$, 100 Hz	TB Med 279 (1)
7:	■	$ED^{RP}_{50}(T)$, 1 Hz	Hemstreet et al (11)
8:		Revised $MPE^{RP}(T)$, 10 Hz	CF Method
9:		$MPE^{RP}(T)$, 10 Hz	TB Med 279 (1)
10:		$MPE^{RP}(T)$, 1 Hz	TB Med 279 (1)
11:		Revised $MPE^{RP}(T)$, 1 Hz	CF Method

The cw $ED_{50}(T)$s and the cw MPE(T)s (lines 1 and 3 respectively) are shown for comparison and reference. The revised permissible exposures provide "margins of safety" that are consistent and comparable to cw conditions for all pulse repetition frequencies. The $MPE^{RP}(T)$ derived by using $C_p = n^{-1/4}$ are the same as the current permissible exposures.

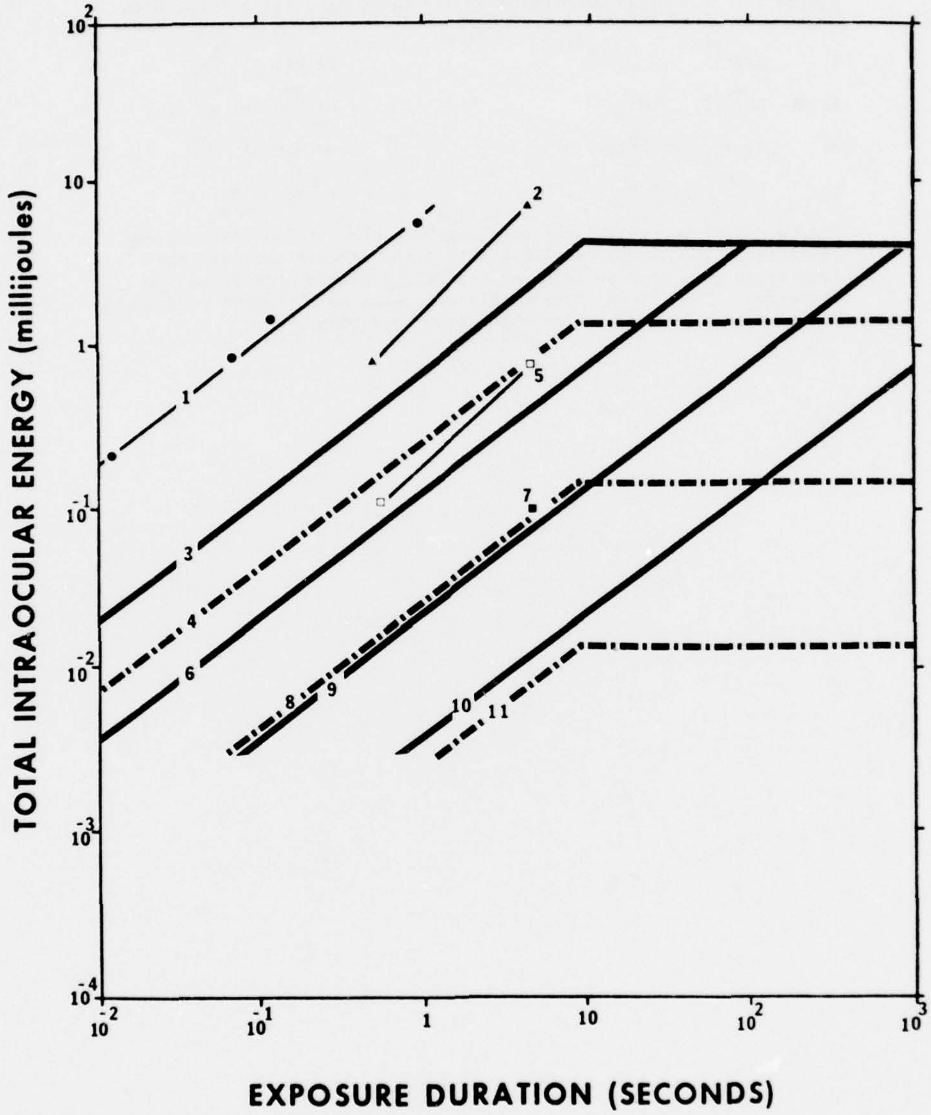
TOTAL INTRAOCULAR ENERGY (millijoules)
EXPOSURE DURATION (SECONDS)
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-2}
10^{-1}
1
10
10^2
10^3
1
2
3
4
5
6
7
8
9
10
11

Figure 12

FIGURE 13: Frequency Doubled Neodymium Laser Repetitive Pulse Data (PRF = 5 Hz, t = 15 nsec, λ = 530 nm)

1:	MPE(T)	TB Med 279 (1)
2: ●	$ED_{50}^{RP}(T)$, 5 Hz	Gibbons et al (14)
3:	Revised $MPE^{RP}(T)$, 5 Hz	CF Method
4:	$MPE^{RP}(T)$, 5 Hz	TB Med 279 (1)

The cw MPE(T) for this laser wavelength is shown for comparison and reference. The experimental $ED_{50}^{RP}(T)$s (line 2) were obtained for long train durations by using a 24 hour ophthalmoscopic response criterion. The current permissible exposures do not provide adequate "margins of safety" for the longer train durations.

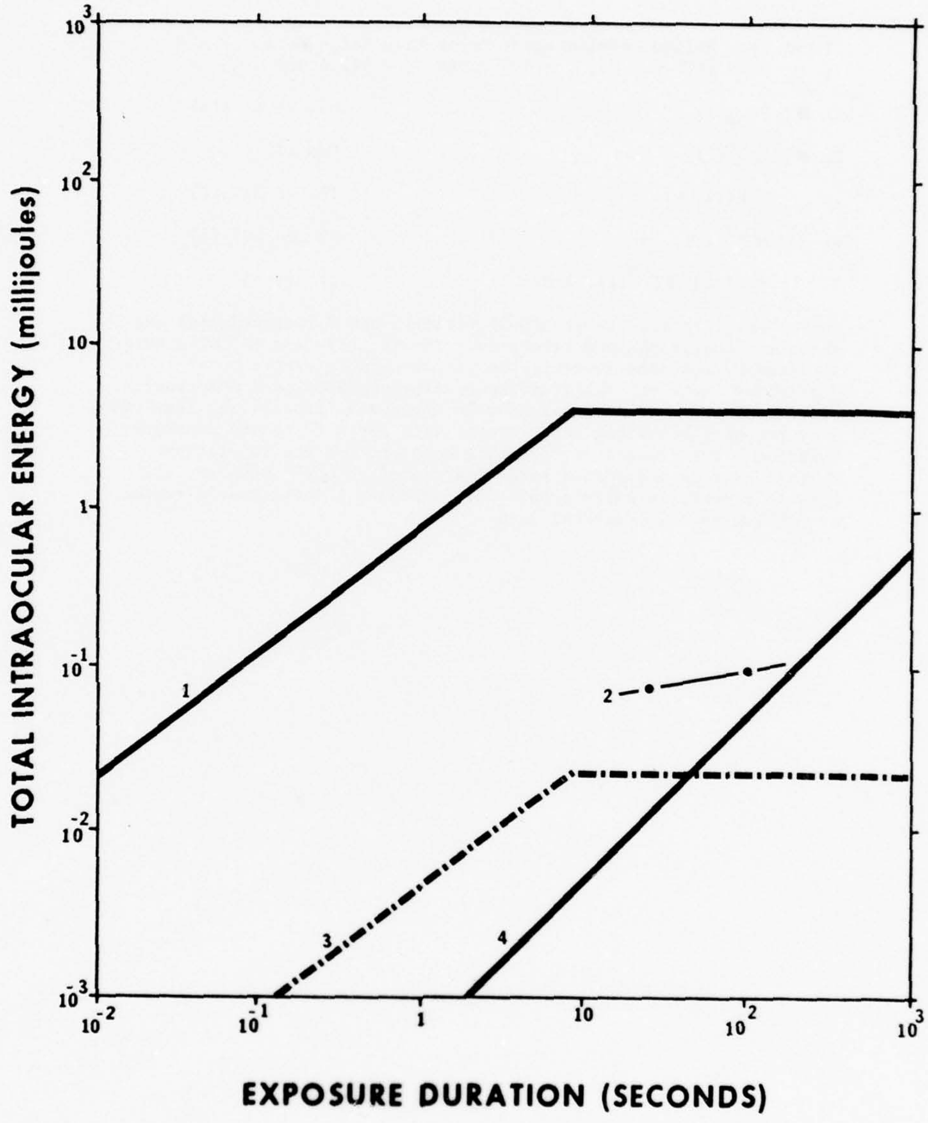
TOTAL INTRAOCULAR ENERGY (millijoules)
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1
10
10^2
10^3
1
2
3
4
EXPOSURE DURATION (SECONDS)

Figure 13

FIGURE 14: Helium Cadmium Laser Repetitive Pulse Data (PRF = 1 Hz, t = 8000 μsec, λ = 441.6 nm)

1: ●	$ED_{50}(T)$	Ham et al (16)
2: ■	$ED_{50}^{RP}(T)$, 1 Hz	Ham (13)
3:	MPE(T)	TB Med 279 (1)
4:	$MPE^{RP}(T)$, 1Hz,	TB Med 279 (1)
5:	Revised $MPE^{RP}(T)$, 1 Hz	CF Method

The cw $ED_{50}(T)$s and the cw MPE(T) (lines 1 and 3 respectively) are shown for comparison and reference. The $ED_{50}(T)$s and $ED_{50}^{RP}(T)$s were obtained by the same investigator for comparable experimental conditions (same retinal irradiance diameter, 500μ, and observation time, 24 hours). The cw permissible exposures (line 3) are less than a factor of 3 below the experimental data for a 10 second exposure duration. The revised permissible exposure for the repetitive pulse condition provides a large "margin of safety"; however, the current repetitive pulse permissible exposure is less than a factor of 5 below the experimental data.

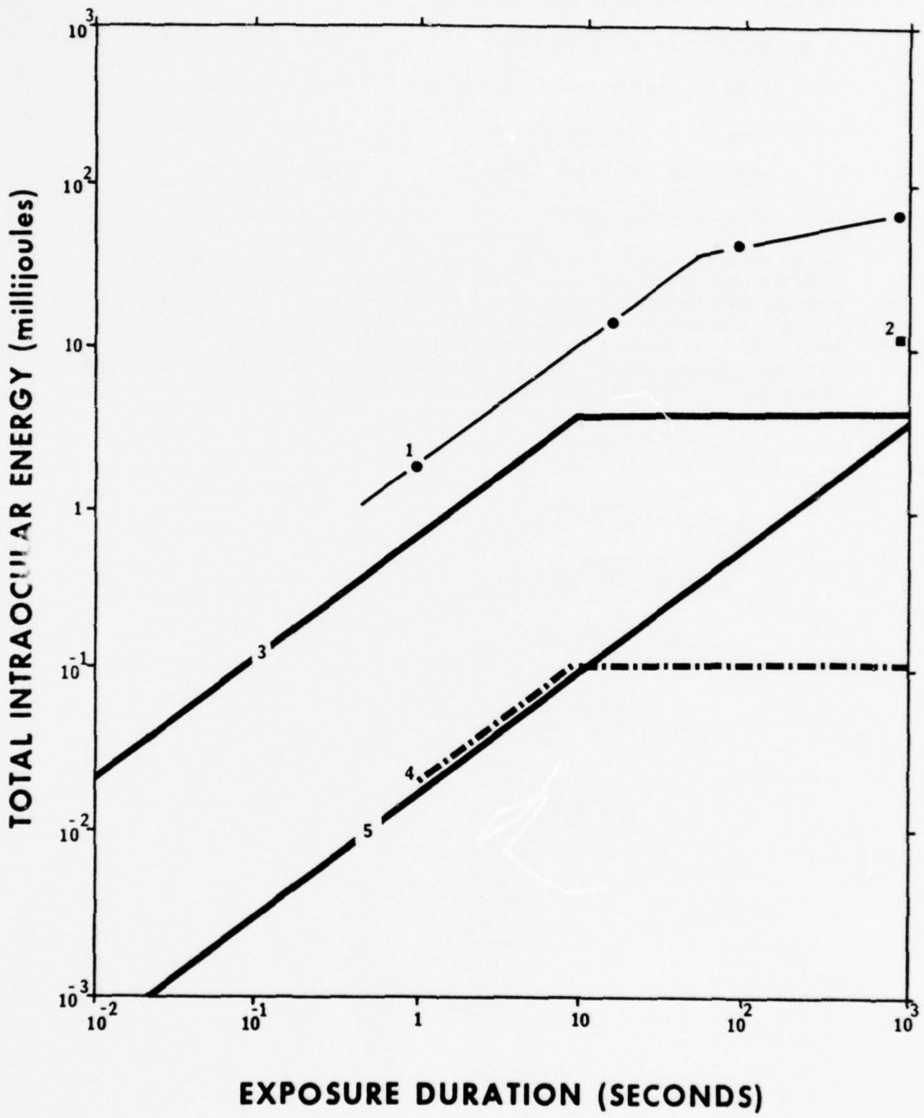
TOTAL INTRAOCULAR ENERGY (millijoules)
EXPOSURE DURATION (SECONDS)
10^3
10^2
10
1
10^-1
10^-2
10^-3
10^-2
10^-1
1
10
10^2
10^3
1
2
3
4
5

Figure 14

FIGURE 15: Experimental data where CF = 1.0

1: ●	$ED_{50}(T)$, cw neodymium laser	Lund et al (7, 8)
○	$ED_{50}^{RP}(T)$, mode locked neodymium laser	Lund et al (17)
2: ☆	$ED_{50}^{RP}(T)$, 120 kHz GaAs laser	Lund et al (17)
3:	MPE(T), cw neodymium laser	TB Med 279 (1)
4:	MPE(T), cw GaAs laser	TB Med 279 (1)

The cw neodymium laser $ED_{50}(T)$s and the mode locked neodymium laser $ED_{50}^{RP}(T)$s are on the same line (line 1). Consequently the cw MPE(T) provides an adequate "margin of safety" for both data sets. The cw GaAs laser MPE(T) (line 4) provides an adequate "margin of safety" for the 120 kHz GaAs laser repetitive pulse data (line 2). The correction factors calculated for both these repetitive pulse conditions exceed 1.0 consequently the cw permissible exposures apply.

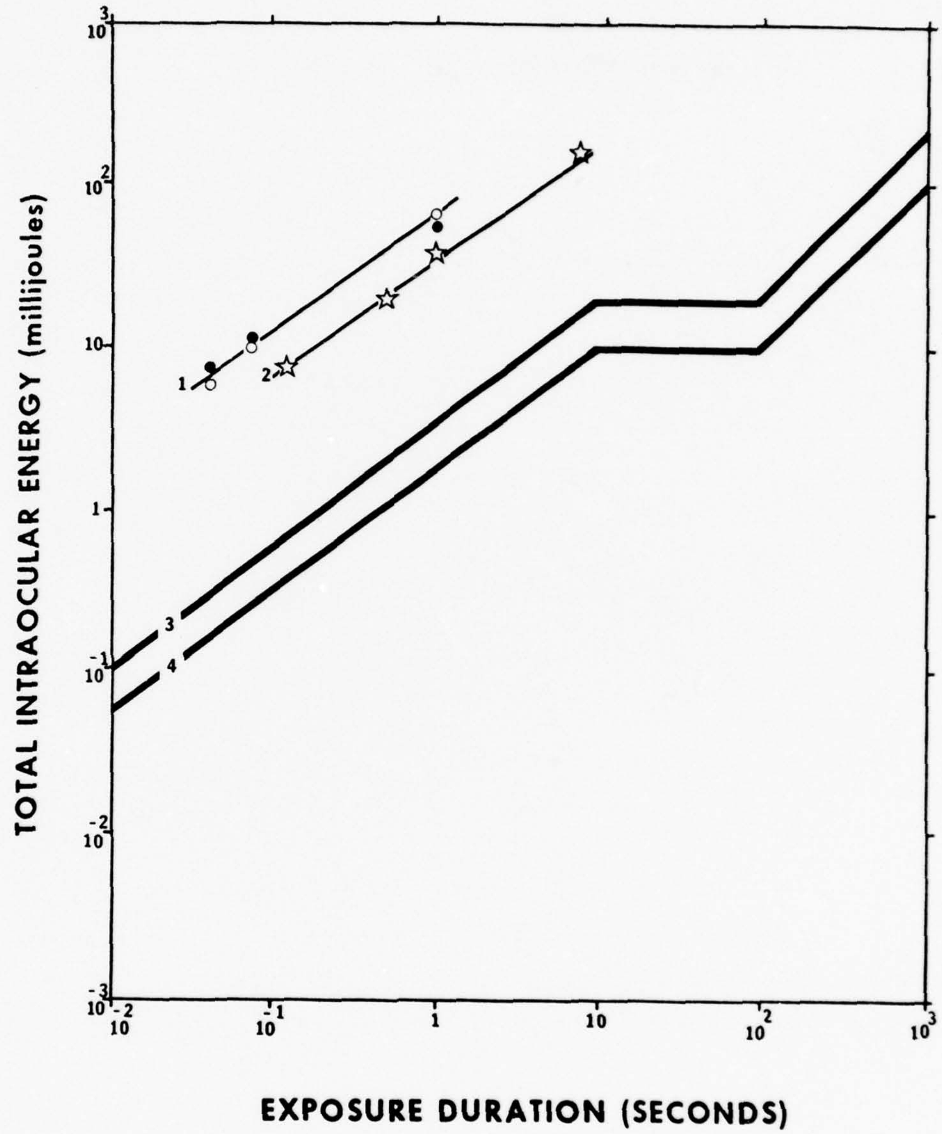
TOTAL INTRAOCULAR ENERGY (millijoules)
EXPOSURE DURATION (SECONDS)
10^{3}
10^{2}
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
1
2
3
4

Figure 15

FIGURE 16: Q as a function of t

Q is the ratio $ED_{50}^{RP}(1/PRF)/ED_{50}(t)$

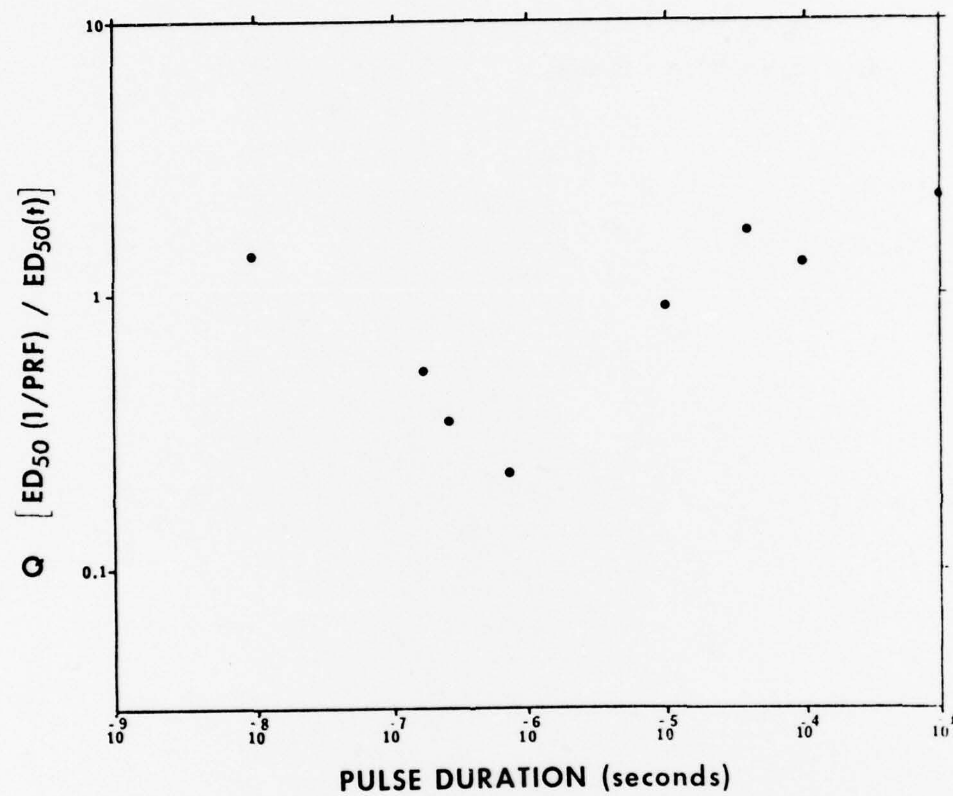
10
1
0.1
Q [ED50 (1/PRF) / ED50(t)]
10^-9
10^-8
10^-7
10^-6
10^-5
10^-4
10^-3
PULSE DURATION (seconds)

Figure 16

FIGURE 17: C_p as a function of PRF

1: C_p, $t < 10\ \mu sec$ TB Med 279 (1)

2: $C_p = n^{-1/4}$, $T = 10$ sec

3: $C_p = n^{-1/4}$, $T = 1$ sec

4: $C_p = n^{-1/4}$, $T = 0.1$ sec

5: $C_p = n^{-1/4}$, $T = 10$ msec

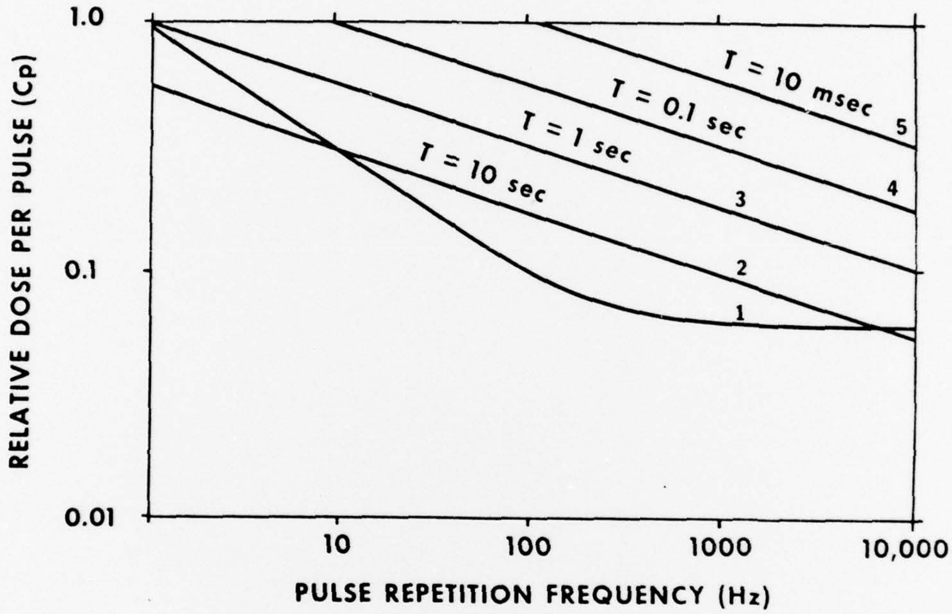
1.0
0.1
0.01
RELATIVE DOSE PER PULSE (Cp)
10
100
1000
10,000
PULSE REPETITION FREQUENCY (Hz)
T = 10 msec
T = 0.1 sec
T = 1 sec
T = 10 sec
1
2
3
4
5

Figure 17

APPENDIX B

TABLE 1. **Repetitive Pulse Neodymium Laser Data**

t ns	PRF Hz	Number Pulses	T ms	$ED_{50}^{RP}(T)$ μJ	$ED_{50}(T)$ μJ	Correction Factor	References
10		1		164.			Ebbers et al (12)
10	10	5	500	785.	37000	2.12×10^{-2}	
10	10	10	1000	1370.	56000	2.45×10^{-2}	
10	20	10	500	1220.	37000	3.30×10^{-2}	
10	20	20	1000	2100.	56000	3.75×10^{-2}	
180		1		130.			Lund et al (5)
180	100	2	20	150.	5000	3.00×10^{-2}	
180	100	3	30	270.	6400	4.22×10^{-2}	
180	1000	2	2	160.	1200	1.33×10^{-1}	
180	1000	3	3	153.	1500	1.02×10^{-1}	
180	1000	6	6	330.	2350	1.40×10^{-1}	
180	1000	74	74	1214.	11200	1.08×10^{-1}	
180	1000	1000	1000	10100.	56000	1.80×10^{-1}	
180	3000	2	0.67	121.	580	2.09×10^{-1}	
180	3000	3	1	131.	750	1.75×10^{-1}	
180	3000	6	2	182.	1200	1.52×10^{-1}	
270		1		28.			Hemstreet et al (9)
270	1	5	5000	31.	150000	2.07×10^{-4}	
270	10	5	500	28.4	37000	7.68×10^{-4}	
270	10	50	5000	128.	150000	8.53×10^{-4}	
270	100	50	500	202.	37000	5.46×10^{-3}	
270	100	500	5000	1283.	150000	8.55×10^{-3}	
270	1000	500	500	918.	37000	2.48×10^{-2}	
270	1000	5000	5000	5940.	150000	3.96×10^{-2}	
700		1		25.			Skeen et al (4)
700	1000	500	500	770.	37000	2.08×10^{-2}	
730		1		25.			Hemstreet et al (9)
730	10000	5000	500	3650.	37000	9.86×10^{-2}	
730	10000	50000	5000	19700	150000	1.31×10^{-1}	
15		1		3.02			Gibbons et al (14)
15	5	150	30000	76.			
15	5	600	120000	96.			

TABLE 2. Repetitive Pulse Argon Laser Data

t μs	PRF Hz	Number Pulses	T ms	$ED_{50}^{RP}(T)$ μJ	$ED_{50}(T)$ μJ	Correction Factor	References
10		1		1.59			Hemstreet et al (11)
10	1	5	5000	1.2	18000	6.67×10^{-5}	
10	1	30	30000	7.9	71000	1.11×10^{-4}	
10	10	5	500	3.4	3500	9.71×10^{-4}	
10	10	5	500	3.25	3500	9.28×10^{-4}	Skeen et al (3)
10	10	50	5000	12.7	17500	7.26×10^{-4}	Hemstreet et al (11)
10	10	300	30000	65.6	71000	9.24×10^{-4}	
10	100	5	50	3.9	650	6.00×10^{-3}	
10	100	50	500	26.	3500	7.43×10^{-3}	
10	100	50	500	10.5	3500	3.00×10^{-3}	Skeen et al (3)
10	1000	500	500	77.5	3500	2.21×10^{-2}	
10	1000	500	500	215.	3500	6.14×10^{-2}	Hemstreet et al (11)
10	1000	5000	5000	1100.	9000	1.22×10^{-1}	
10	10000	500	50	195.	650	3.00×10^{-1}	
10	10000	5000	500	555.	3500	1.59×10^{-1}	Skeen et al (3)
10	10000	50000	5000	9500.	18000	5.28×10^{-1}	Hemstreet et al (11)
10	10000	300000	30000	33500.	71000	4.72×10^{-1}	
40		1		2.04			Gibbons et al (10)
40	10	5	500	6.0	3500	1.71×10^{-3}	Hemstreet et al (11)
40	100	10	100	20.	1100	1.82×10^{-2}	Gibbons et al (10)
40	100	50	500	50.	3500	1.43×10^{-2}	
40	100	100	1000	40.	6000	6.67×10^{-3}	
40	1000	500	500	500.	3500	1.43×10^{-1}	
40	10000	5000	500	2600.	3500	7.43×10^{-1}	Hemstreet et al (11)
100		1		4.6			Hemstreet et al (11)
100	10	5	500	12.	3500	3.43×10^{-3}	
100	100	50	500	99.	3500	2.83×10^{-2}	
100	1000	500	500	965.	3500	2.75×10^{-1}	
1000		1		19.9			
1000	1	5	5000	99.	18000	5.50×10^{-3}	
1000	10	50	5000	735.	18000	4.08×10^{-2}	
1000	100	500	5000	7050.	18000	3.92×10^{-1}	

TABLE 3. Argon and Neodymium Laser Data for CW Exposures

T ms	$ED_{50}(T)$ μJ	λ nm	Reference
12	222	514.5	Bresnick et al (6)
70	875	514.5	
125	1437	514.5	
1000	5500	514.5	
8	2700	1060.	Lund et al (8)
38	7500	1060.	
69	11300	1060.	
1000	56300	1060.	

TABLE 4. The Factor Q

PRF Hz	t μs	$ED_{50}^{RP}(1/PRF)$ μJ	$ED_{50}(t)$ μJ	Q	Reference
10	.010	239	164	1.46	Ebbers et al (12)
20	.010	219	164	1.34	
1000	.180	70.5	130	.54	Lund et al (5)
10	.270	7.65	28	.27	Hemstreet et al (9)
100	.270	11.1	28	.40	
1000	.270	9.3	28	.33	
10000	.730	6.02	28	.22	Hemstreet et al (9)
1	10	.49	1.59	.31	Hemstreet et al (11)
10	10	.87	1.59	.55	
100	10	1.28	1.59	.80	
1000	10	1.94	1.59	1.22	
10000	10	2.43	1.59	1.53	
10	40	1.79	2.04	.88	Hemstreet et al (11)
100	40	3.19	2.04	1.56	Gibbons et al (10)
1000	40	4.73	2.04	2.32	
10000	40	4.37	2.04	2.14	
10	100	3.59	4.6	.78	Hemstreet et al (11)
100	100	5.27	4.6	1.15	
1000	100	9.13	4.6	1.98	
1	1000	29.6	19.9	1.49	Hemstreet et al (11)
10	1000	39.1	19.9	1.96	
100	1000	66.6	19.9	3.35	

TABLE 5. Comparison of MPEs for Low PRFs

PRF Hz	Number Pulses	T s	$ED_{50}^{RP}(T)/n$ μJ/pulse	$ED_{50}^{RP}(T)$ μJ	Correction Factor Method CF MPE(T) μJ	S	Current Standard MPE(TOTP) μJ	S
.067 *	2	30.	1.51	3.02	9.03×10^{-3}	335	.207	15
.4	2	5.	0.70	1.40	3.24×10^{-2}	43	.207	7
4.	2	0.5	1.10	2.24	5.76×10^{-2}	39	.207	11
40.	2	0.05	1.02	2.07	1.02×10^{-1}	20	.207	10
.1	3	30.	1.51	4.50	3.10×10^{-2}	49	.281	16
.6	3	5.	0.40	1.22	4.86×10^{-2}	25	.281	4
6. *	3	0.5	0.85	2.55	8.65×10^{-2}	30	.281	9
60. *	3	0.05	0.90	2.70	1.54×10^{-1}	18	.281	10
.167 *	5	30.	1.38	6.90	2.25×10^{-2}	302	.412	17
1.	5	5.	0.24	1.20	8.10×10^{-2}	15	.412	3
10.	5	0.5	0.68	3.40	1.44×10^{-1}	24	.412	8
100.	5	0.05	0.80	3.90	2.56×10^{-1}	15	.412	9
.3 *	10	30.	0.84	8.40	9.29×10^{-2}	90	.693	12
2. *	10	5.	0.24	2.40	4.04×10^{-2}	208	.693	3
20. *	10	0.5	0.55	5.50	2.88×10^{-1}	19	.693	8
160. *	10	0.063	0.71	7.10	4.85×10^{-1}	15	.693	10

Note: The data on this Table were taken from Figure 14 (page 41) of Hemstreet et al (11). The asterisks (*) denote those data which were obtained by interpolation methods (see addendum on page 14 of this report).

GLOSSARY

C_p ---------- a factor by which the single pulse permissible exposure is multiplied to obtain the permissible radiant exposure per individual pules in a repetitive pulse train.

CF(t) ------- the ratio $ED_{50}^{RP}(T)/ED_{50}(T)$. The magnitude of this correction factor is dependent upon the pulse repetition frequency and the duration t of each individual pulse in the repetitive pulse train.

$ED_{50}(T)$ ----- effective dose for a 0.50 probability of ophthalmoscopically observing a lesion for a single cw exposure of total duration T.

$ED_{50}^{RP}(T)$ ----- effective dose for a 0.50 probability of ophthalmoscopically observing a lesion for a repetitive pulse train of total duration T.

$ED_{50}^{RP}(1/PRF)$ - the repetitive pulse ED_{50} evaluated by extrapolation to a train length equal to the reciprocal of the pulse repetition frequency.

PRF --------- pulse repetition frequency.

Hz ---------- hertz (pulses per second).

MPE(T) ------ the maximum permissible exposure for a single exposure of duration T.

$MPE^{RP}(T)$ ---- the maximum permissible exposure for a repetitive pulse train of total duration T.

n ----------- the number of pulses in a pulse train of duration T (n = PRF T).

Q ----------- the ratio $ED_{50}^{RP}(1/PRF)/ED_{50}(t)$.

R ----------- the ratio CF(t)/CF(10 μs).

S ----------- the factor which when multiplied by the maximum permissible exposure for a given exposure condition gives the ED_{50}.

T ----------- the exposure duration. For repetitive pulse conditions, T denotes the total duration of the pulse train.

t ----------- the duration of each individual pulse in the repetitive pulse train.

TIE --------- the total intraocular energy.

TOTP -------- total on time pulse. For a repetitive pulse train, TOTP is equal to the number of pulses n times the duration t of each individual pulse (TOTP = n t = PRF T t).

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